Revisiting the Blackwood River and Hardy Inlet

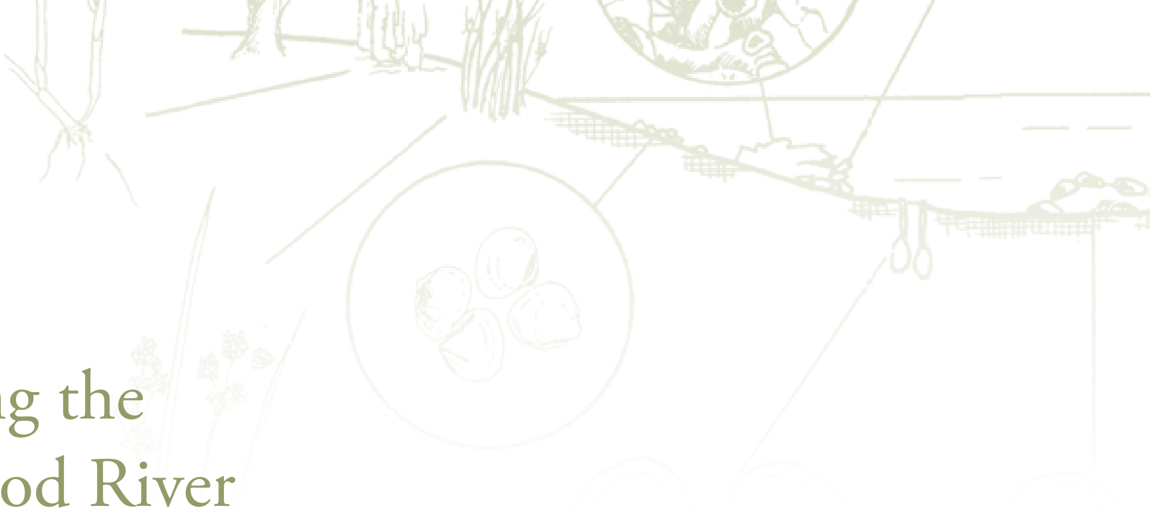
40 years of change

Anne Brearley

An environmental review of the Blackwood River
estuary Western Australia 1974–2010

National Trust

Ernest Hodgkin Trust
for Estuary Education and Research



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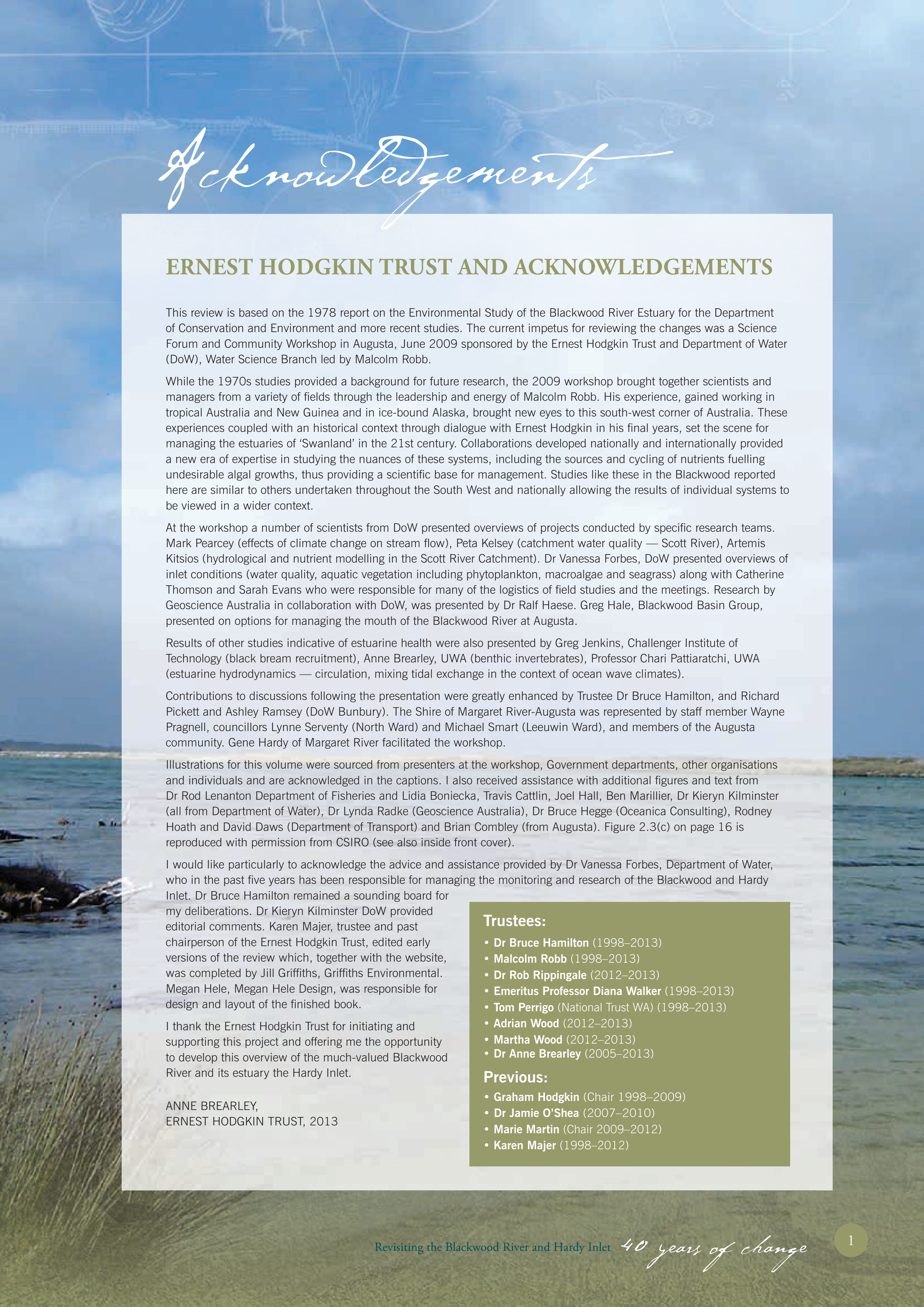


Acknowledgements

ERNEST HODGKIN TRUST AND ACKNOWLEDGEMENTS

This review is based on the 1978 report on the Environmental Study of the Blackwood River Estuary for the Department of Conservation and Environment and more recent studies. The current impetus for reviewing the changes was a Science Forum and Community Workshop in Augusta, June 2009 sponsored by the Ernest Hodgkin Trust and Department of Water (DoW), Water Science Branch led by Malcolm Robb.

While the 1970s studies provided a background for future research, the 2009 workshop brought together scientists and managers from a variety of fields through the leadership and energy of Malcolm Robb. His experience, gained working in tropical Australia and New Guinea and in ice-bound Alaska, brought new eyes to this south-west corner of Australia. These experiences coupled with an historical context through dialogue with Ernest Hodgkin in his final years, set the scene for managing the estuaries of 'Swanland' in the 21st century. Collaborations developed nationally and internationally provided a new era of expertise in studying the nuances of these systems, including the sources and cycling of nutrients fuelling undesirable algal growths, thus providing a scientific base for management. Studies like these in the Blackwood reported here are similar to others undertaken throughout the South West and nationally allowing the results of individual systems to be viewed in a wider context.

At the workshop a number of scientists from DoW presented overviews of projects conducted by specific research teams. Mark Pearcey (effects of climate change on stream flow), Peta Kelsey (catchment water quality — Scott River), Artemis Kitsios (hydrological and nutrient modelling in the Scott River Catchment). Dr Vanessa Forbes, DoW presented overviews of inlet conditions (water quality, aquatic vegetation including phytoplankton, macroalgae and seagrass) along with Catherine Thomson and Sarah Evans who were responsible for many of the logistics of field studies and the meetings. Research by Geoscience Australia in collaboration with DoW, was presented by Dr Ralf Haese. Greg Hale, Blackwood Basin Group, presented on options for managing the mouth of the Blackwood River at Augusta.

Results of other studies indicative of estuarine health were also presented by Greg Jenkins, Challenger Institute of Technology (black bream recruitment), Anne Brearley, UWA (benthic invertebrates), Professor Chari Pattiaratchi, UWA (estuarine hydrodynamics — circulation, mixing tidal exchange in the context of ocean wave climates).

Contributions to discussions following the presentation were greatly enhanced by Trustee Dr Bruce Hamilton, and Richard Pickett and Ashley Ramsey (DoW Bunbury). The Shire of Margaret River-Augusta was represented by staff member Wayne Pragnell, councillors Lynne Serventy (North Ward) and Michael Smart (Leeuwin Ward), and members of the Augusta community. Gene Hardy of Margaret River facilitated the workshop.

Illustrations for this volume were sourced from presenters at the workshop, Government departments, other organisations and individuals and are acknowledged in the captions. I also received assistance with additional figures and text from Dr Rod Lenanton Department of Fisheries and Lidia Boniecka, Travis Cattlin, Joel Hall, Ben Marillier, Dr Kieryn Kilminster (all from Department of Water), Dr Lynda Radke (Geoscience Australia), Dr Bruce Hegge (Oceanica Consulting), Rodney Hoath and David Daws (Department of Transport) and Brian Combley (from Augusta). Figure 2.3(c) on page 16 is reproduced with permission from CSIRO (see also inside front cover).

I would like particularly to acknowledge the advice and assistance provided by Dr Vanessa Forbes, Department of Water, who in the past five years has been responsible for managing the monitoring and research of the Blackwood and Hardy Inlet. Dr Bruce Hamilton remained a sounding board for my deliberations. Dr Kieryn Kilminster DoW provided editorial comments. Karen Majer, trustee and past chairperson of the Ernest Hodgkin Trust, edited early versions of the review which, together with the website, was completed by Jill Griffiths, Griffiths Environmental. Megan Hele, Megan Hele Design, was responsible for design and layout of the finished book.

I thank the Ernest Hodgkin Trust for initiating and supporting this project and offering me the opportunity to develop this overview of the much-valued Blackwood River and its estuary the Hardy Inlet.

ANNE BREARLEY,
ERNEST HODGKIN TRUST, 2013

Prelude

"To make sound strategic decisions about how to manage estuaries to conserve their environmental and cultural values, we need to understand the importance of how they have changed in response both to natural environmental factors and to human activities. Otherwise, we may well expend resources managing one factor while another unmanaged could lead to the demise of estuaries. It is vital to undertake the research necessary to provide a broad strategic understanding for estuary management beyond such immediate problems as eutrophication." (Hodgkin and Hesp, 1998).

Revisiting the Blackwood — 40 Years of Change was produced by the Ernest Hodgkin Trust for Estuary Education and Research (the Trust) to celebrate the work and inspiration of Ernest Pease Hodgkin (1908–1998). The publication marks more than ten years of activity by the Trust in promoting estuarine science and education.

In 1973, Ernest Hodgkin (1908–1998) retired as the reader in zoology at the University of Western Australia. He continued working as an environmental consultant and developed a deep love and appreciation for the estuaries of the south-west of Australia. As coordinator of the Blackwood Estuary study in the early 1970s, then as leader of the Peel-Harvey estuarine system study from 1976, he pioneered an interdisciplinary approach that set the scene for the way we approach waterway problems today.

'Hodge', as he was fondly referred to, had a long interest in estuaries. As a zoologist he was interested in their fauna, which he investigated with his students through the 1950s and beyond. These studies generated Hodge's wider fascination with ecology along the coast, in the rivers and where river meets sea in the estuaries, and the context of place and response to the landscape. Hodgkin and his colleagues were particularly active in the decades following the Second World War (1950–1970s). In this period, population growth and increased mechanisation led to dramatic changes in the landscape, with clearing, land use changes and fertilisers all playing a part. The resulting erosion, salinisation and algal blooms were generally not welcomed by the community, and brought calls for these problems to be investigated. The need for scientifically-based management became apparent.

Coordinating large teams of researchers was to dominate Hodge's 'retirement years' 1975–1998. His fascination with the estuaries in the South West, their similarities and differences, resulted in a series of booklets, the Estuarine Study Series, written with Ruth Clark. This documentation of the different systems led to consideration of the processes leading to their formation and changes over long time scales — ideas formulated in his last paper on the evolution of estuaries, co-authored with Patrick Hesp and published shortly after his death (Hodgkin and Hesp, 1999).

In September 1998, shortly before his death at the age of 90, Hodgkin set up a trust fund through the National Trust (WA) and made a substantial bequest from his estate to continue the work that was important to him — research and education to promote sound management of Western Australia's estuaries. The Ernest Hodgkin Trust for Estuary Education and Research was formed to continue Hodgkin's research and promotion of Western Australian estuaries.

Before his death, Hodge had planned a book. It was to ensure that a wider view of estuaries and how they respond to natural processes and human activities was available beyond the scientific community for the people of Western Australia. An integral aspect was promoting a 'Sense of Place', a concept developed by George Seddon in his 1972 book of that title, which detailed the natural history of the Swan River and coastal plain. Hodge suggested that 'Swanland', a long forgotten name for the south-west corner of Western Australia, from Shark Bay to Israelite Bay on the Great Australia Bight (Taylor 1915), would be a good title. The book ***Ernest Hodgkin's Swanland*** *Estuaries and Coastal Lagoons of South-western Australia* was published in 2005 by The University of Western Australia Press (Brearley 2005), bringing Hodge's plan to fruition.

Revisiting the Blackwood — 40 Years of Change follows and expands on Swanland, presenting an overview of our present knowledge about the greater Blackwood River system and including the Hardy Inlet. It is largely based on Hodge's report of the 1974–1975 studies (Hodgkin 1978), bringing it up to date with present knowledge and highlighting changes since the 1970s.

The Blackwood was undoubtedly Ernest Hodgkin's favourite river. He talked fondly of this '*Magnificent and Peaceful river*' (quoting Hasluck 1955, from a letter by Georgiana Molloy to Captain Mangles in January 1839) in a radio interview recorded by the ABC not long before his death. The Blackwood's place in his heart had been clear to his associates for a long time.

View to East Augusta, January 2012. Anne Brearley.

Ernest Hodgkin's love of the Blackwood is shared by many. It is one of our largest rivers, flowing across the gently undulating land of the eastern wheatbelt, home of the open eucalypt mallee woodlands and salt lakes, westwards through steeper valley country with higher rainfall and increasingly gigantic trees, and finally entering the Southern Ocean at Flinders Bay in the lee of Cape Leeuwin.

A study of the Blackwood River Estuary 1974–1975, commissioned by the Environmental Protection Authority of WA (EPA) and overseen by the Estuarine and Marine Advisory Committee (EMAC), was conducted in response to an application for mining mineral sands in and around Augusta and the Hardy Inlet.

It is worth noting that in the 1970s, when the first study of the Blackwood system was undertaken, the issue was very particular — to assess the impact of dredging in the estuary seawards of Molloy Island and on the eastern bank of the Scott Coastal Plain.

"Little is known about the ecology of Hardy Inlet and the possible effects of the mining proposal on it. No scientific references can be found relating to this particular estuary and only limited research has been done in other possibly comparable areas. Most of this latter work has been specific to particular organisms rather than the overall structure and balance of the estuary system." (Department of Environmental Protection 1973).

The study had two primary objectives: Firstly, in the short term, to attempt to predict the probable effects of mining and dredging in the estuary and environs. And in the long term, to understand the working of the Blackwood estuary ecosystem as the basis for making decisions about the management of this and other estuaries of south-west Australia.

The research also examined the dynamics of fish and bird populations, the foods utilised by these populations and the abundance and distribution in the system, and the role of water plants and human usage of the estuary. Each of these components was assessed in terms of dredging impacts.

The study marked a formative period in estuarine science. It approached the system as a whole, from source to mouth, using expertise from a range of disciplines: geology, hydrology, botany, zoology and social science. This led to investigations of interacting processes and features — an 'ecosystem approach' — to understand how a system develops and functions.

The report of the study by Ernest P. Hodgkin 1978, *An Environmental Study of the Blackwood River Estuary Western Australia 1974–1975*, summarised 15 technical reports and a number of scientific papers prepared by scientists from government and university departments. '*The present report is concerned primarily with the second objective, that is, with a general assessment of the estuary ecosystem*'. Historically, this was Report No 1 of the Department of Conservation and Environment. A separate report '*The Anticipated Effects of Dredging in the Blackwood Estuary*' was prepared by EMAC and submitted to the EPA.

The Blackwood 1974–1975 study set the scene for an integrated approach to the understanding of estuaries and integrated catchment management, which considered the physical and biological landscape with land uses and impacts to maintain the overall health of the river and catchment.

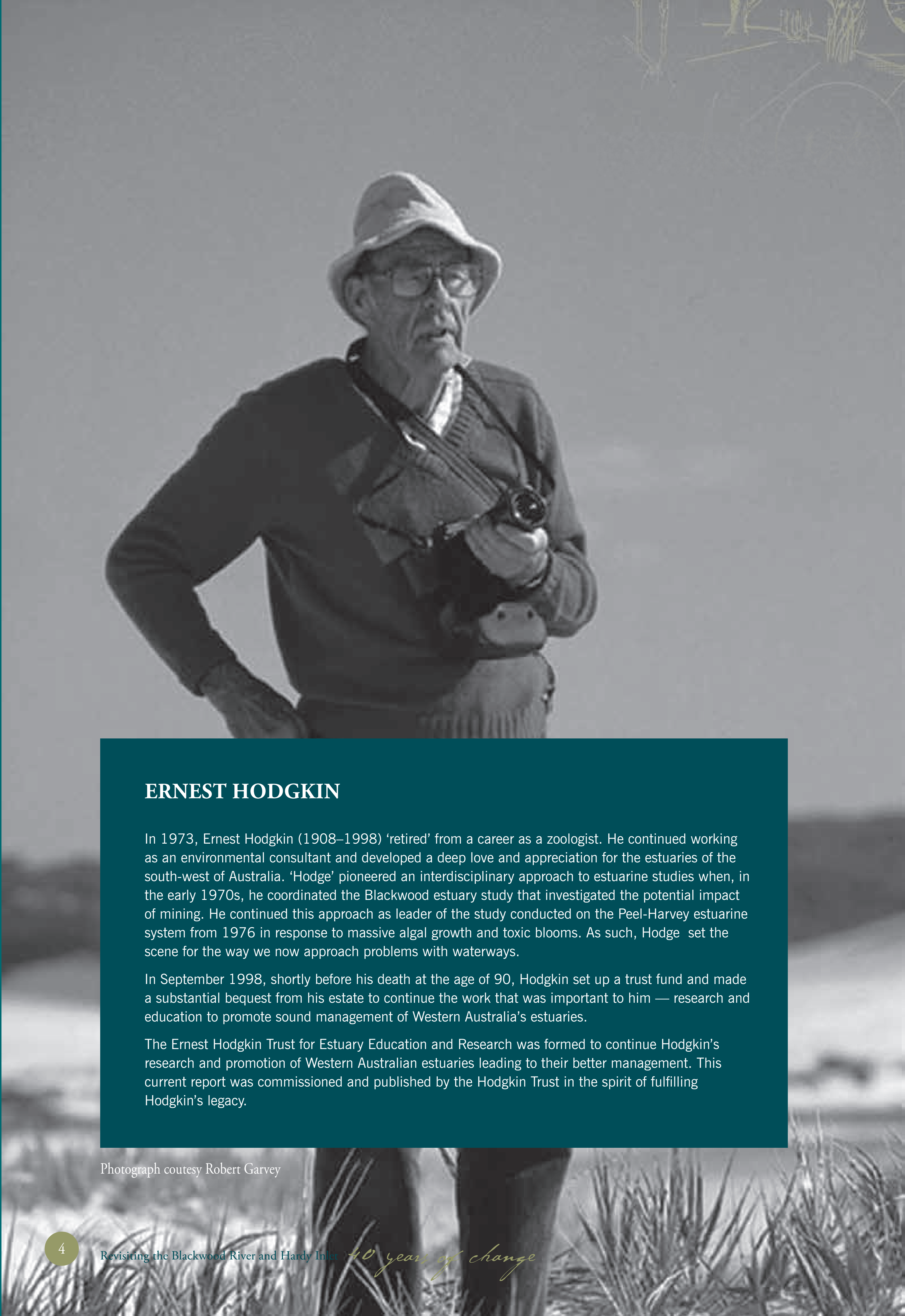
Revisiting the Blackwood — 40 Years of Change incorporates current information with the findings from 1974–1975 and celebrates the growth of knowledge that is available to underpin good management of the whole system for the people, for the future. In so doing, it fulfils the vision of Ernest Hodgkin's Trust for Estuary Education and Research.

ERNEST HODGKIN

In 1973, Ernest Hodgkin (1908–1998) 'retired' from a career as a zoologist. He continued working as an environmental consultant and developed a deep love and appreciation for the estuaries of the south-west of Australia. 'Hodge' pioneered an interdisciplinary approach to estuarine studies when, in the early 1970s, he coordinated the Blackwood estuary study that investigated the potential impact of mining. He continued this approach as leader of the study conducted on the Peel-Harvey estuarine system from 1976 in response to massive algal growth and toxic blooms. As such, Hodge set the scene for the way we now approach problems with waterways.

In September 1998, shortly before his death at the age of 90, Hodgkin set up a trust fund and made a substantial bequest from his estate to continue the work that was important to him — research and education to promote sound management of Western Australia's estuaries.

The Ernest Hodgkin Trust for Estuary Education and Research was formed to continue Hodgkin's research and promotion of Western Australian estuaries leading to their better management. This current report was commissioned and published by the Hodgkin Trust in the spirit of fulfilling Hodgkin's legacy.



Photograph coutesy Robert Garvey

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Entrance channel Hardy Inlet, previously the Deadwater January 2012. A. Brearley

Chapter 1

SETTING THE SCENE

Chapter 1

Setting the scene

In the early-mid 1970s, Ernest Hodgkin led a detailed scientific study of the Blackwood River and Hardy Inlet. The reports from that and subsequent studies provided a baseline on the health of the system. Indeed, Hodgkin found a healthy system and, using the number of mollusc species as a criterion for quality, wrote that *the Blackwood compares favourably with the other estuaries of south western Australia. With the evidence adduced (above) of long term stability, there is every reason to believe that this is a healthy, resilient, ecosystem in balance with the extreme hydrological conditions, despite the relatively few species when compared with more marine estuaries elsewhere.*

Hodgkin compared the Blackwood-Hardy system to the Nornalup, which is a more marine environment with more marine species, and the Peel, which has a more impoverished fauna. He noted: *It is unlikely that the Blackwood estuary will ever approximate either of these extremes under the present climatic regime. Also the sort of cyclical variation, which is observed in the Swan estuary, is not expected in the Blackwood because of the much greater river run-off here, even in a dry year*.

Hodgkin related the estuary's health to climate stability and a continuity of rainfall. But what of the system in a changing climatic regime? Is the Blackwood a healthy and resilient ecosystem today?

This review, 40 years after Hodgkin's initial studies, seeks to answer these questions.

Limestone outcrop East Augusta June 2011. Courtesy. M. Cambridge. The area lies within a Shire Recreation Reserve. A section with marine fossils deposited when sea level was higher is a Geoheritage Site.

1.1 Hodgkin's Blackwood — Hardy Inlet and Blackwood River in the 1970s

The variability of salinity is a feature of estuarine systems. Hodgkin noted that this was particularly important to the habitat and biota in the Blackwood, because the change from fresh to marine was evident even in the lower estuary, and the organisms living there were subjected to one or another extreme for months at a time. The estuary could be classified as a 'seasonal estuary'. Hodgkin regarded salinity as of 'overriding importance', but also suggested that other environmental factors, such as the volume of river flow, temperature, nature of the substrates, strength of the currents and tides while 'not readily separable from salinity', were influencing the composition and abundance of the biota. Biological studies were a major component of the 1974–1975 studies and regarded as of great importance to understanding the consequences of dredging.

Phytoplankton were considered to make only a small contribution to primary production in the Blackwood as cell densities were very low and chlorophyll was scarcely measurable. *'It is thought that this is attributable principally to the relatively low nutrient levels and the large tidal volume of the lower estuary'.* Zooplankton, the principle herbivores of phytoplankton, were similarly sparse.

Macroalgae and aquatic plants were found to be neither diverse nor abundant due in part to the extremes of salinity and the lack of hard substrates. The freshwater species *Potamogeton pectinatus* was found to extend downstream almost to the basin in spring, when it was abundant at Molloy Island, but disappeared with the advance of brackish water. *Ruppia*, a species with wide salinity tolerance, was the most abundant of the aquatic plants *'in the inlet, basin and in the marginal shallows of the tidal river in summer; it is also the dominant species in the Deadwater and Swan Lake* and of particular importance as a contributor to the primary production through grazing by swans. While not eaten to any great extent by estuarine fauna, *Ruppia* and plants growing in the marginal swamps were considered major contributors to the detritus, supporting the microbial communities used by bottom dwelling (benthic) deposit feeders and ultimately fish and bird predators.

The aquatic fauna were grouped into categories according to time and breeding within the estuary. The 'true estuarine' animals, with self-maintaining populations within the estuary, were those favouring shallow calm waters and able to contend with the extremes of salinity. Of the 55 species of benthic invertebrates collected, 40 were considered estuarine. Thirteen species dominated the fauna: two polychaete worms, seven molluscs (four bivalves and three gastropods), two crustaceans and one insect. These were considered the main food resource for fish and birds.

Waterbird use of the estuary was observed to vary seasonally, generally relating to the availability of other suitable habitats. Many waterfowl used the estuary as a refuge when other inland waters were dry over summer. Waders migrating from the northern hemisphere in summer also used the shallow areas of the estuary for feeding. The estuary and the surrounding bushland provided habitat for a number of other birds regarded as permanent residents.

Fish (57 species) were recorded and grouped according to estuary use. Six were true estuarine fish, one of which, the black bream, was quantitatively the most important in the ecosystem. The non-resident fish, that is those that spawned in the sea and entered the estuary as juveniles or adults, were grouped according to tolerance of low salinity water. They were regarded as part of the larger marine populations. Studies of fish diets were undertaken and related to the environmental conditions. Surveys of recreational and commercial fishing activity were also conducted.

Hodgkin regarded *Man's* principle role in the aquatic ecosystem as a predator on the fish. Despite not having an estimate of the total fish biomass, he suggested that it was *'unlikely that human predation makes a serious impact, as most species were a small part of the much larger population moving freely along the coastline of south western Australia'*.

In a summary of the long period human occupation he noted *'that although the aboriginal population in this extreme south west corner of the continent was probably sparser than that of the warmer more open forest of the coastal plain to the north, it was sufficiently dense to have had a profound effect on the forest vegetation and coastal scrub, and in consequence also on erosion and runoff to the estuary'*. Early European developments in the 1830s –1849 also affected the landscape through sheep and cattle grazing in the more open forest. Clearing was limited to areas used for building houses and producing food. The estuary was used for transport and for fishing to supplement the diet. Grazing leases issued in the 1850s for summer grazing, while not generally involving clearing, did increase both deliberate and uncontrolled burning regimes, thus changing the vegetation.

Changes in the catchment accelerated with timber milling from 1870 to 1900, tourism in the 1900s, the World War I Group Settlement Scheme 1921–1931 and the subsequent clearing of 27,865 acres, and the opening of the Flinders Bay railway in 1925. The World War II Service Land Settlement led to further clearing of small farms that were later amalgamated into larger more economic units. Cyclical shifts occurred between dairying and beef cattle.

The Hodgkin report noted that *"The expansion of agricultural activities has affected the estuary in two ways; through the increased runoff and by damage to marginal vegetation. Clearing must have resulted in both in some increase in direct runoff to the estuary via Chapman Brook, McLarty Creek, Scott River and other small tributaries and an increased nutrient input from grazing land. Both must have had a small impact on the estuarine environment.*

ABOVE: Australian Pelican. Courtesy K. Coates.
BELOW: Common estuary shrimp *Palaemonetes* among *Ruppia*. E.P. Hodgkin.

Destruction of marginal vegetation and cattle grazing to the water's edge is potentially more serious. There is increased risk of damage to banks during flood periods, resulting in further destruction of vegetation, erosion of banks, and increased sedimentation downstream. As yet this sort of damage has not been great, but once started it can accelerate rapidly. The sort of ruthless clearing of the banks recently carried out near Alexandra Bridge is especially to be deplored.

The Deadwater is probably the result of quite small scale human interference with the estuarine system early this century, with the further result of the access to Swan Lake (Hodgkin 1976). More recently dredging the boat channel in 1956 and again in 1973 have had their effects on both the physical and biological features of the estuary.

The expansion of tourism …has brought with it human usage of the estuary. As yet, this is not on a scale to have caused the great changes that can be seen in the Swan and Murray River estuaries, though already the banks and marginal vegetation have a "used" look in a few places. The Blackwood estuary is appreciated by many for its peace and unspoilt natural beauty, amenities which are not consistent with uncontrolled usage by large numbers of people and power boats. As always in such circumstances the very attraction for which the place is valued can be destroyed by their devotees. Some control will have to be exercised over the use of the river and its banks if this is not to happen." (Hodgkin 1978).

1.2 Hardy Inlet in 2012

Forty years later a lot has changed. From an estuarine research and management perspective there are now more government agencies with particular expertise and responsibilities. However these are subject to considerable, frequent structural changes and reorganisation. As a result, recommendations to avoid environmental degradation are not always implemented in response to pressures of development, changing political visions, or expediency. Perhaps the greatest concern is the loss of an understanding of the characteristics of healthy functioning estuarine systems.

Water-flows in the Blackwood are now much lower. The reasons are manyfold but relate to increased use of water through capture in dams and extraction through bores, and to the decrease in rainfall. Rising salinity now affects crop growth and water use for stock. In the past, saline flows from the upper catchment were diluted to some extent by higher rainfall in the forest regions of the middle and lower catchment. Redirection of saline groundwater into the eastern tributaries of the Blackwood, coupled with reduced precipitation in the lower catchment, has increased river salinity downstream. Clearing has continued, although perhaps not on the same scale as in the first half of the 20th century. Activity on exposed soils has increased along with the application of fertilisers to boost production. More livestock with access to watercourses foul the water and aggravate bank erosion, which increases the sediments and organic nutrient loads that flow to the estuary. The water entering the rivers and estuary carries more nutrients and organic matter. Fish are more difficult to catch, raising the question of conditions in the system and fish health as well as the issue of over harvesting of the fish populations.

The changes now evident in the estuaries and the rivers that flow to them are varied and appear to be increasing at an alarming rate:

- water quality has declined;
- across the catchment erosion is rampant, leading to siltation;
- large areas of the upper and middle catchment are saline and unproductive;
- river flows are lower, originally in response to dams and weirs on tributaries but also increasingly due to abstraction of groundwater, and compounded by the decrease in rainfall, higher temperatures and evaporation rates that in the south west, are likely to be ongoing.

The estuarine biota are also changing:

- fish stocks are in decline in response to *in situ* environmental changes in water quality;
- algal blooms are more common. They may simply be aesthetically unpleasant and smelly, or they may be toxic and detrimental to the health of fish and people;
- low oxygen conditions occur due to salinity stratification, decay of organic matter and algal respiration;
- more common use of toxins, chemical sprays and poisons;
- higher fishing pressure and depletion of brood stocks.

The overarching feature is too many people wanting ‘a piece’ of the estuary, either the water that flows to it, the foreshore for building, the waterways for boating and skiing or the resources of fish and crabs. Today we are confronted with balancing the many issues to maintain a healthy and sustainable system. *As always in such circumstances, the very attraction for which the place is valued can be destroyed by their devotees.* (Hodgkin 1978).

Inlet banks with rushes, grass trees *Kingia australis*, marri *Corymbia calophylla*, salt tolerant paperbarks *Melaleuca cuticularis* and flooded gums *Eucalyptus rudis* April 2008. A. Brearley.

1.3 This Report

The aim of this document ***Revisiting the Blackwood** — **40 Years of Change*** is to provide a contextual framework of information about the system to support the various documents of scientists, government and research agencies with specific expertise.

Perhaps we can again go back to Ernest Hodgkin’s summary at the end of his 1978 report and consider the possibility that this current document provides some answer to his question.

This study has examined the various elements of the biota, the significance of the various habitat types to these, the importance of the several geomorphic units to the estuary, and the impact of changing environmental conditions. This has been done on the basis of one year of investigation, a year which had a greater than average river runoff. How far, then, are our findings of 1974–1975 representative of the long term status of the system, and what stability has the system within the human times scale of a few decades?

Purpose

This report revisits the 1970s Blackwood studies and reviews the most recent research and what it reveals about changes in the system over the past 40 years.

While the 1974–1975 studies were defined by the questions of dredging impacts, the results provided a broad and detailed background of the Blackwood-Hardy and a wider understanding of other systems in the south west. Now 40 years later, and in light of more comprehensive studies of many of our estuaries, we need to redefine the problems or the rationale for current research and this synthesis. Behind this lie questions of: *What do we value? What we would like the system to be in the future? Do we know enough to manage it? and ultimately What are the best management options?*

In the 1970s much of the information collected by Hodgkin and his colleagues was based on the marked seasonality of the system with fresh flows a major influence on the system’s biota. While they commented on effects of land degradation and algal blooms in other systems, these were not evident in the Hardy in 1975.

Sues Bridge area. The height of the bridge illustrates the depth of the valley and height of expected floodwaters October 2010. A. Brearley.

Downstream of the bridge, the waters may overtop the riverbanks and run through channels alongside the main channel, January 2012. A. Brearley.

In bringing the 1978 report up-to-date, this current report expands the purpose to address the wider impacts evident today. Although the focus is on the estuarine part of the system, the changes are dictated by the wider landscape, and what is happening upstream.

The overarching theme of any estuary work is WATER. How large and consistent are the flows? Where does the water come from, how salty is it and what sediments and nutrients does it carry to the estuary? In essence this means that there is a greater emphasis on the catchment, on the landscape, geology and soils, how the land is used, what water is still available for the river flows to the estuary, what is brought to the estuary by the water, and how we manage the downstream at the end of the line. These are all factors that Hodgkin referred to as emerging issues.

Scope

This document follows the approach of the 1978 report, presenting a summary of knowledge of the system at that time and an overview of the recent research and current conditions.

Chapter 2 focuses on the catchment and the factors that influence the volume and quality of water flowing to the Hardy Inlet. Given that the rainfall influences the water flowing to the estuary, the implications of a changeable climate to river flows are described (Pearcey 2010). The landscape of the Blackwood and Scott rivers is examined in terms of the underlying geological structure, water storage in aquifers used to supplement agricultural production and domestic supplies, and the interaction of aquifers and stream flows (DOW 2009 abc 2010). We then present an overview of the issues of salinity, acidification, and the ability of soils to retain nutrients that now affect the widespread catchment of the Blackwood and the Scott Coastal Plain that surrounds Hardy Inlet. This is followed by a more detailed account of land use in the two river catchments that influence the water, nutrients and sediment that reach the Hardy, and modelling of different activities, including fertilisers in the catchment, as a basis for managing water quality (Kelsey and Kitsios 2007; Hall 2011; Marillier 2011). This research supports the Hardy Inlet Water Quality Improvement Plan Stage one — Scott River catchment (White 2012).

Chapter 3 focuses on the physical features of the estuary. The first section describes how the different areas were classified according to geomorphology and concentrates on the sediments. It presents overviews of the estuary's development over millions of years, the properties of the sediment that reflect the geological structure, formation and sediment accumulating in the Holocene, and changes over the last 6000 years (developed from Hodgkin (1978) and Sas (1974)). The more recent sedimentary change is the growth of the sandbar across the ocean channel in response to onshore movement of sand caused by oceanic swells, river and tidal flows. This has occurred twice since European settlement. The chapter presents an overview of tidal changes within the system, based on the 1974–1975 reports and the interplay of river flow and tides on the salinity within the system (Pattiaratchi 2010). Investigations by Geoscience Australia (Haese *et al*. 2010) on sedimentation within the basin following the development of agriculture add to the story of the sediments and examination of what happens to nutrients that enter the system. The chapter also reviews the preliminary studies documenting sediment nutrients (Hale *et al*. 2000) conducted in response to growing concerns about algal blooms. These are followed by the 2007–2008 surveys and experimental studies of nutrient fluxes into the water column (Haese *et al*. 2010). Finally, the chapter examines water quality in terms of the types and concentrations of nutrients and the evidence of recycling of nutrients from the sediment in some parts of the estuary (White 2012; Forbes 2011).

Chapter 4 describes the biological aspects of the estuary. For the past 12 years the Department of Water has monitored nutrients and phytoplankton in the estuary, but no longer does. These results are presented and compared with the 1970s. A description of the benthic aquatic vegetation, macro- and micro-algae and seagrasses in the 1970s and more recently (Hale *et al*. 2000; Wilson and Paling 2008) follows. Information on the fauna is based on the 1978 report and studies of invertebrates (Wallace 1976) and fish (Caputi and Lenanton 1976; Lenanton *et al*. 1976), and the recent investigations on invertebrates (Brearley 2010) and fish (Jenkins *et al*. 2000; Department of Fisheries 2004; Valesini *et al*. 2007 and 2009; Prior and Beckley 2007; Potter *et. al*. 2008; Gardner *et. al*. 2010). As there have been no published studies of the birds using the estuary over the last four decades, a few questions of responses to environmental conditions are raised.

Agricultural land, pine plantation and state forest, Lower Blackwood, near Karridale, 2009.

Courtesy Greg Hales, Blackwood Basin Group.

Chapter 2

CATCHMENT OF THE GREATER BLACKWOOD

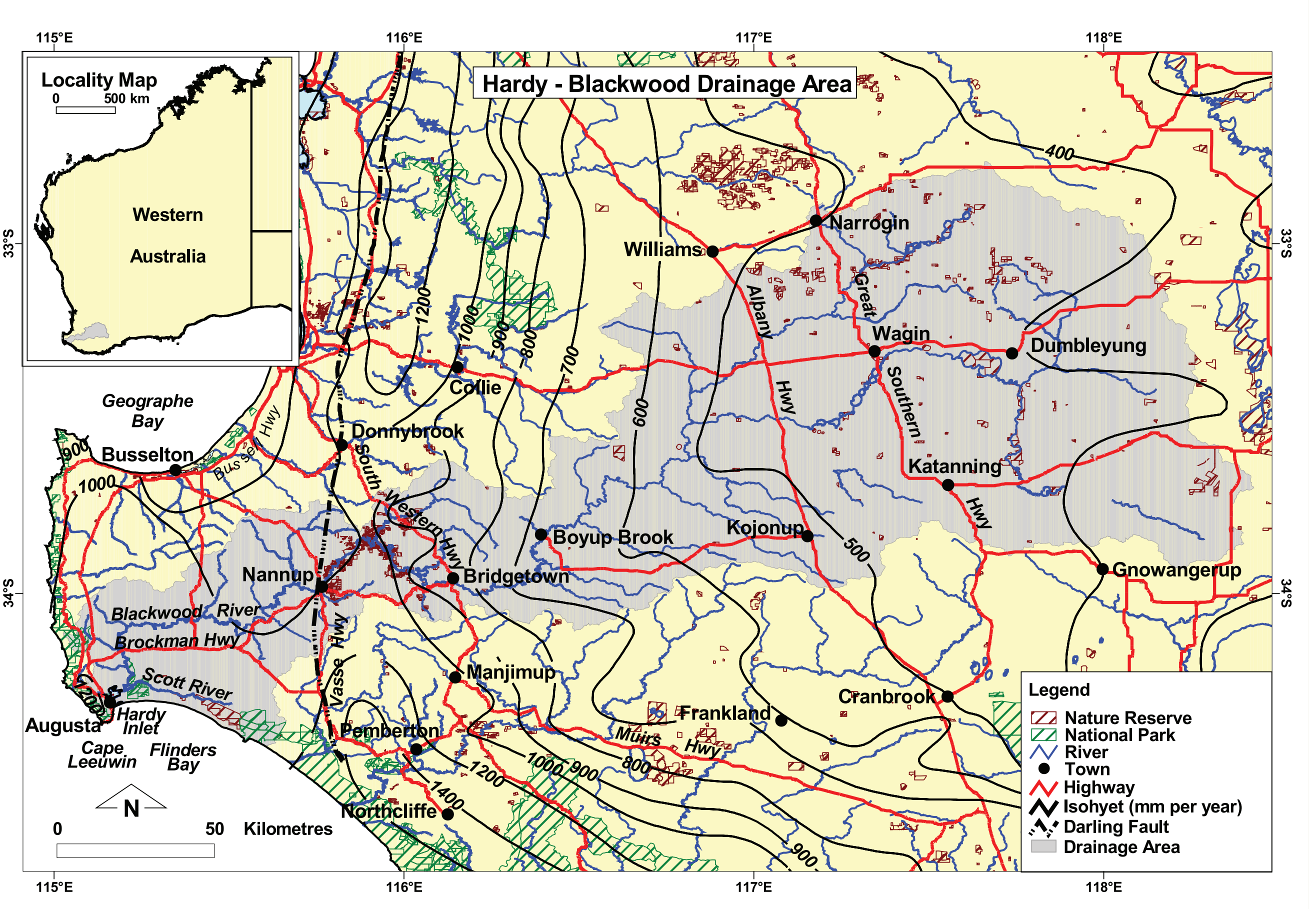
Catchment of the greater Blackwood

2.1 Changeable climate — Rainfall and river flows

Declining rainfall

Covering 2.23 million hectares, the greater Blackwood River catchment is the second largest catchment in the South West. Only the Avon, which is approximately 11.6 million ha, is larger (DoW 2012). The catchment can be divided into two components — the Blackwood River catchment of 21,400 km^2 and the Scott River catchment covering 670 km^2. While the Blackwood catchment is much larger than the Scott, this is not reflected in its flow volume. The Scott, which lies in an area of higher rainfall, has a comparatively larger flow and contributes some 15% of the flow to the Hardy. Differences in soil and land use in the two catchments also influence the quality of water entering the estuary.

Hardy Inlet lies in temperate Western Australia, in the highest rainfall region of the South West (1100–1200 mm per year). Much of the expansive eastern Blackwood catchment is much drier, receiving about 300–400 mm per year (Map 2.1). Evaporation rates also vary greatly across the catchment from 900 mm in the west to 1900 mm in the east. In general most of the rain falls in the colder winter months. However thunderstorms and disipating tropical cyclones in summer occasionally bring heavy falls, including some of the largest recorded flows to the Hardy, such as those associated with cyclones Bruno-Errol in January 1982. This flow may be the largest since European settlement (Bowman and Ruprecht 2000).



Map 2.1 Hardy Inlet – Blackwood and Scott Rivers catchment. From *SWANLAND* (Brearley 2005). Drafted by DoW for the Ernest Hodgkin Trust 2005.

The greatest contributions to stream and river flow are derived from rain falling in the lower catchment, and this is the region where rainfall in the future is expected to be much lower. Rainfall has already reduced substantially and this decline is now widely acknowledged. Sourcing of water for industry, agriculture and urban use is already a problem and competition for a dwindling resource is growing so rapidly that water allocation is a major topic of debate (Department of Climate Change and Energy Efficiency 2011).

Climate changes over time. Fossils embedded in limestone and sediment along the coast provide evidence that, in the past 6000 years, sea levels have been three metres higher than they are now, before falling to present level 2000–3000 years ago. Usually this is viewed in a historic context, for example the eras of glaciation with the formation and melting of the ice caps. (See *SWANLAND*, Chapter 1, Understanding Swanland: Flat coastal landscape of water and wind, Box 2.1 An older estuary hidden under Guildford and Box 2.2 Seashells at Peppermint Grove).

Weather and rainfall vary from year to year. We are used to early breaking rains, good sustained falls and bumper harvests versus late break of seasons, low patchy rainfall and poor harvests, and variability in water stored for cities, industry and agriculture. However until recently there has been a reluctance to view these year-to-year differences in the wider context of long-term trends. Rainfall decline within the wider issues of global warming, climate change and rising sea levels are now pervasive themes in the scientific literature, media and wider community. Although these issues were not widely talked of 20 years ago, Ernest Hodgkin and Ruth Clark did voice them in Volume 2 of the Estuarine Studies Series in 1988 and 1999, reporting a decrease of 200 mm in mean annual rainfall at Walpole between 1956 and 1988.

Decreasing rainfall is clearly evident in the records from Cape Leeuwin, where rainfall has decreased by about 20–25% (Figure 2.1a). In the Blackwood catchment, river flow has changed markedly, particularly since the 1940s. The last major flood occurred in summer 1982 when flow from the middle and upper lower catchment delivered 338 GL to the system in the first six days, which was 62% of the annual flow for that year. Even though the peak flow rate was high overall, the flow volume was relatively moderate. Since 1957, water flow volumes have been high on only five occasions and there have been only four occasions when the flow rate was high. The driest period on record covers the past 11 years (Figure 2.1b). (See also Section 2.5 River flows).

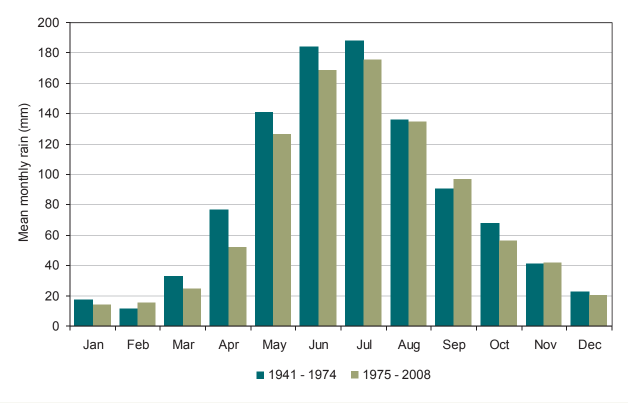


Figure 2.2 Timing of rainfall in south-western Australia.
Courtesy M. Pearcey DoW. Based on records from the Cape Leeuwin Lighthouse (BOM #009518) and data from the Queensland DNRM/BOM SILO patch point database.

In addition to the decline in rainfall, there has been a marked shift in the timing of rainfall, with the break of season occurring later (Figure 2.2). This has severe implications for future agricultural production. It could also change the timing of river flow and salinity in the estuaries, with flushing and the freshwater phase establishing later in the colder months.

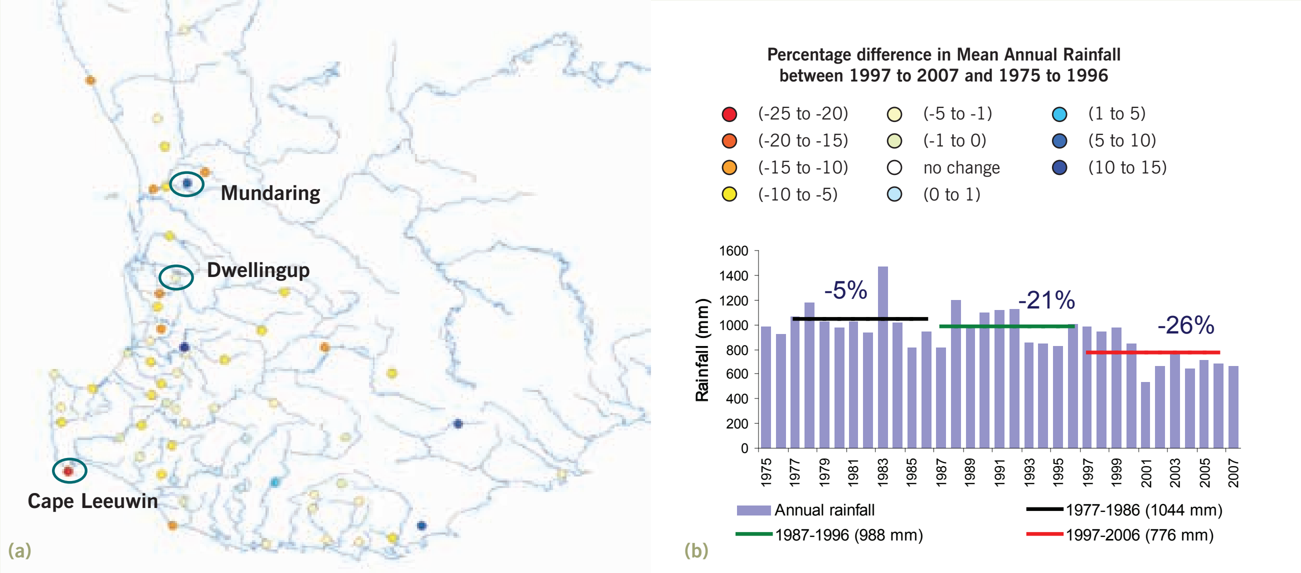


Figure 2.1 (a) Rainfall decline at sixty stations throughout the south west in the periods 1975–1996 and 1997–2007. Rainfall decreased at 85% of sites. At 26 sites rainfall decreased 5–10%, and at eight sites rainfall decline was greater than 10%. **(b)** Rainfall in the Augusta area 1975–2007.
Courtesy M. Pearcey DoW.

Rainfall to river flow

Stream and river flow reflect the amount of rainfall, however the connection can vary depending on where the rain falls, the type of landscape, soils and vegetation and how water is retained or released from the catchment. Dry periods also affect streamflow either because soil moisture needs to be restored before runoff occurs or because dry soils repel moisture resulting in sheet flow. In the context of a changing climate, rainfall and temperature both influence streamflow through effects on evaporation rates and plant growth.

Predicting stream flow

Stream flow projections can be estimated by the equation (DoW 2010):

$$\Delta Q = 3 \times \Delta P - 0.5 \times \Delta T$$

Streamflow % change = 3 x rainfall change % – 0.5 x temperature change %

ΔQ is % change in streamflow.
ΔP is % rainfall change = (future - current) ÷ current) x 100.
ΔT is % temperature change = (future – current) ÷ current) x 100.

Seasonal patterns have also changed markedly; flow volume in early winter has diminished, many streams in high rainfall areas no longer flow in summer, and pools once permanent are dry (Figure 2.3 a, b, and c). Changes like these are particularly devastating for some habitat specific plant and animal communities but also pose a threat to the biota across the whole landscape.

Streamflow can be viewed in two ways, as the volume over a particular time or as the rate of flow during floods. Streamflow in the Blackwood Catchment is presently highly variable and projections of the response to declining rainfall and rising temperatures, while similarly variable, indicate that flows could decline by 12.5–63% in the next 40 or so years (Figure 2.3 b). However there is also likely to be a two to four times increase in flood flows due to compounding influences of clearing, rising groundwater and salinity. The time of clearing and impacts vary, developing more rapidly in the higher rainfall area than in the drier upper catchment where salinity is not expected to peak until 2050. As such, increased flood flows may not be apparent until the full extent of salinisation is reached in the South West (Bowman and Ruprecht 2000). Overall these changes represent a switch from regular winter flows to episodic events of increasing intensity and frequency.

Changes in the flushing through streams, rivers and estuaries have the capacity to produce a range of effects. These include the removal or retention of sediments and materials within the system, the amount of fresh water, overall salinity and perhaps impacts on the species dependant on a regular period of fresh water or reduced salinity. The decrease in volume, rate and timing of flow from the catchment will also affect the progression of saline marine water moving upstream. Changes in volume and timing of flow may be particularly significant in the Blackwood where the scenario of large regular freshwater flows described in 1974–1975 has dominated the estuarine dynamics.

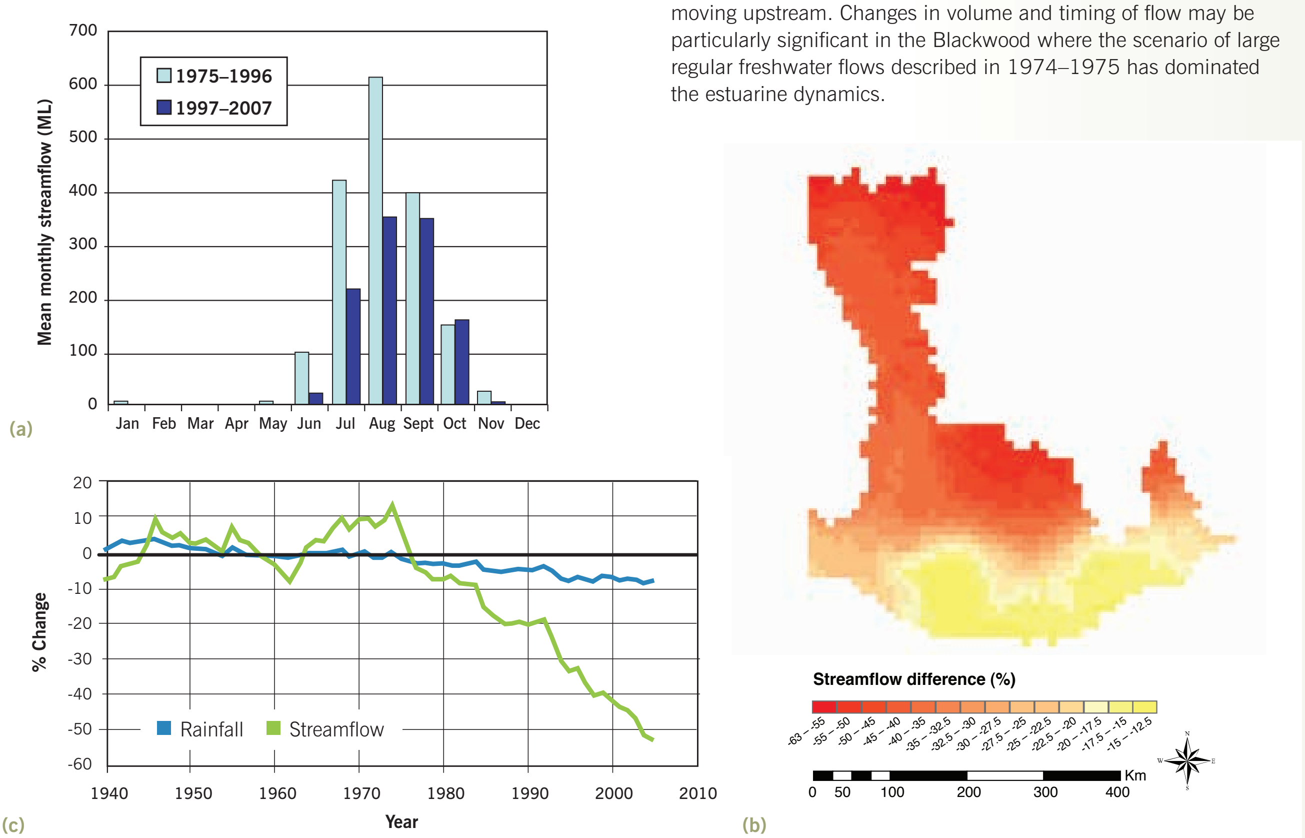


Figure 2.3 Top left **(a)** Streamflow (mean monthly) in high rainfall forested catchments in the south west showing major reductions in early winter. Some streams no longer flow in summer. Right **(b)** Potential decrease in streamflow in the Blackwood River catchment to 2050. (Fig 15 of DoW 2010). Bottom left **(c)** Yearly streamflow into Perth's Dams (May–April) illustrating non-linear relationship between rainfall decrease and streamflow reduction. Data WA Water Corporation and BOM National Climate Centre. CSIRO and BOM 2007. © CSIRO, Reproduced with permission from http://www.climatechangeinaustralia.gov.au/.

2.2 Geomorphology

Blackwood River catchment

The landscape of the Blackwood River and its tributaries reflects a long history of climatic changes and weathering of the underlying geological structure (Beard 1999; De Silva *et al*. 2000). The uppermost catchments on the Darling Plateau, about 300 metres above sea level and east of the Darling Fault, lie in the ancient core of the country (Map 2.1 and 2.2). To the west of the fault the catchment traverses the sedimentary Perth Basin.

East of the Meckering Fault Line, the river flows through undulating country where the broad flat valleys contain mainly sandy soils that overlie a lateritic basement rich in hydrated iron oxides. Rainfall is at its lowest, evaporation is high and drainage is poor, with large areas covered by salt lakes. Generally the upper catchment does not contribute flow in to the Blackwood unless Lake Dumbleyung fills and overflows, which it has only done three times since 1870 and has not been observed since 1964 (De Silva *et al*. 2000).

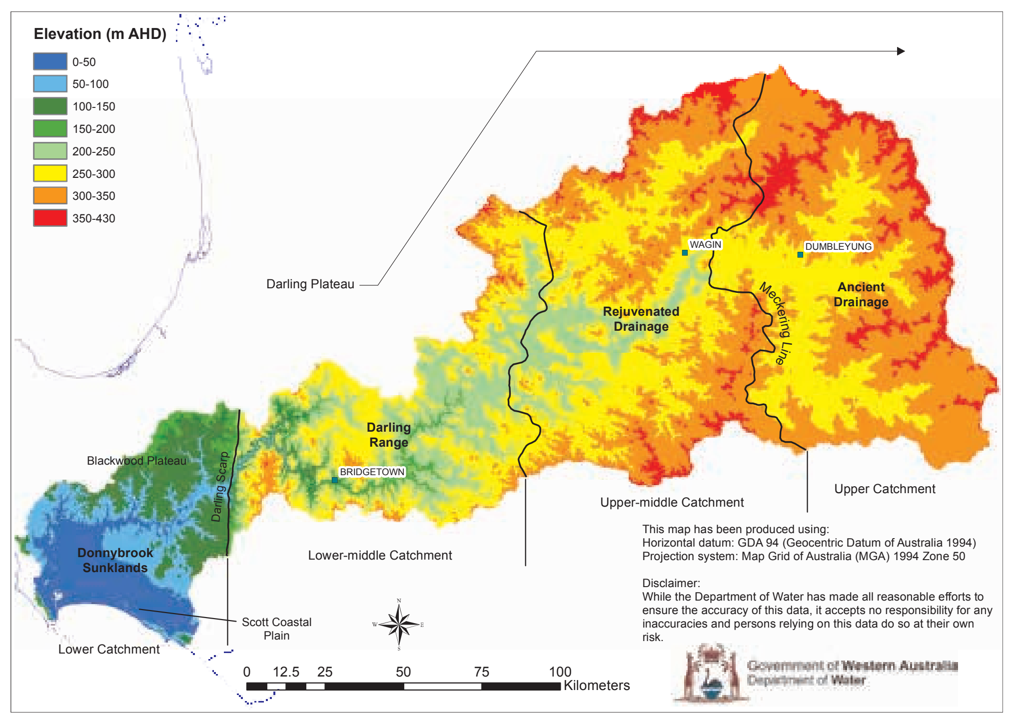
West of Wagin-Katanning the underlying laterite is more exposed, rainfall is higher and the watercourses are more defined, but only isolated brackish pools remain as summer progresses. Further west, downstream of Boyup Brook, lateritic hills surround the river valleys where the underlying granitic rocks lie exposed. With higher rainfall, river flow is more sustained, with some flow evident throughout the year. West of Nannup and between the Darling Fault and the Dunsborough Fault, the river meanders in deep steep-banked channels through a gently undulating landscape of sediments accumulated over 150 million years (Map 2.3). This area, known as the Blackwood Plateau (100–200 m AHD), is also referred to as the Bunbury Trough or Donnybrook Sunklands. The Scott Coastal Plain drained by the Scott River lies to the south.

Scott River and Coastal Plain

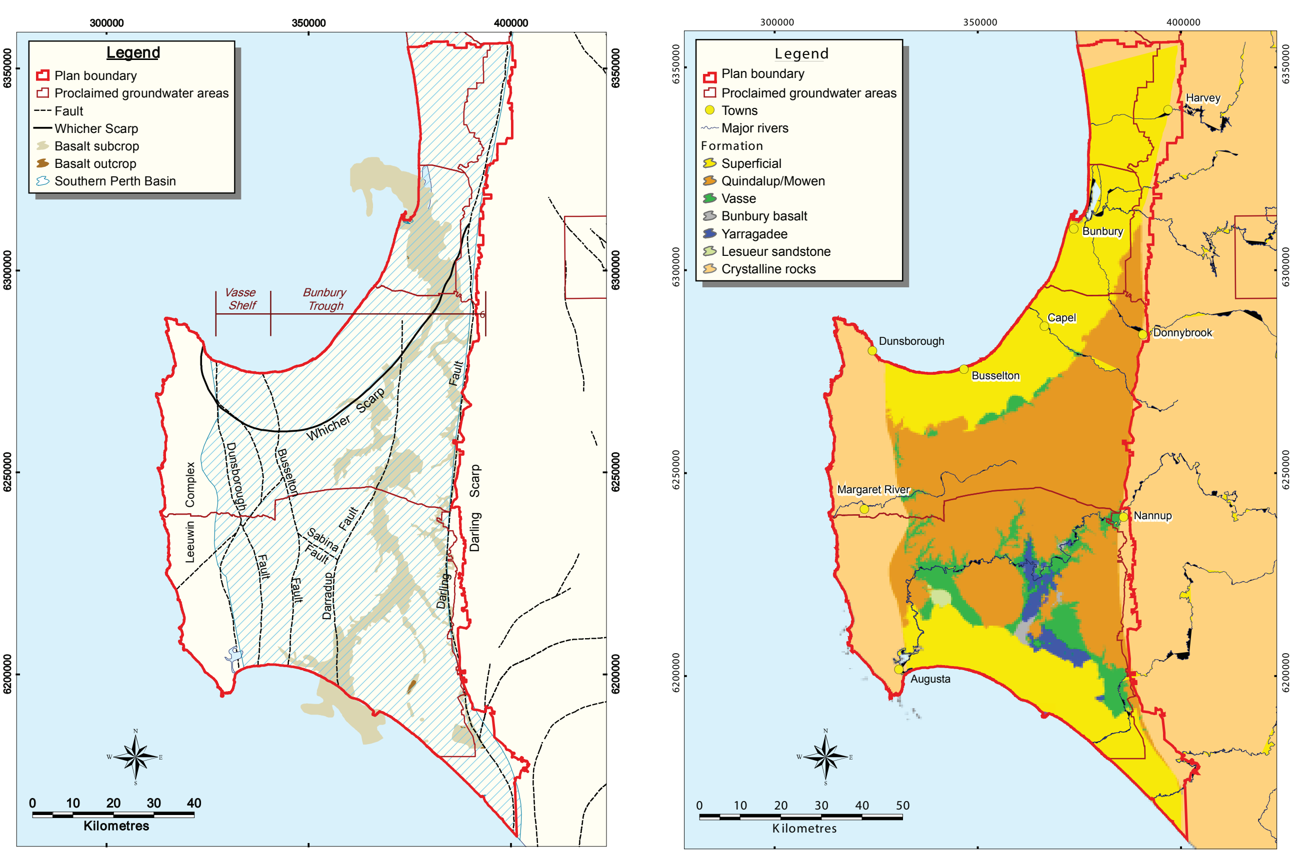
The Scott Coastal Plain is a low-lying area up to 17 km wide that extents about 90 km from the Hardy Inlet to the south east near Point D'Entrecasteaux and Windy Harbour, an area of about 69,100 ha. The boundaries, marked by the Darling Fault and Plateau to the east, Blackwood Plateau to the north, and the Leeuwin-Naturaliste Ridge — Margaret River Plateau to the west, are quite steep except for the western edge of the Blackwood Plateau, known as the Barlee Scarp, where the gradient is lower. In the west, the plain is drained by the Blackwood and Scott rivers. In the east, it is drained by the Donnelly River and four permanent freshwater lakes (Quitjup, Jasper, Wilson and Smith), which define an area of internal drainage within the D'Entrecasteaux National Park. In winter much of the plain is waterlogged, the boundaries of many wetlands are not defined and flow often spreads out across the country as sheet drainage (Baxter 1977; Baddock 1995).

The Scott Coastal Plain is similar in structure to the Swan Coastal Plain, with four shoreline dune systems and offshore reef lines. These systems reflect different periods of sea level due to the growth and contraction of the polar ice caps about one to two million years ago in the Pleistocene.

The Scott River runs parallel to the coast in a broad flat valley (Scott River Plain) between the dune lines. The oldest two dunes north of Scott River are highly leached with peaty acid quartz soil. South of the river the coastal influence and dune structure are more obvious. This is the area where deposits of heavy minerals, principally ilmenite, led to the first mineral claims of the 1970s — the impetus for the Blackwood studies of that time and the titanium mines later developed at Jangardup (1994) and Beenup (1994–1999).



Map 2.2 Zone of ancient drainage (Upper Catchment), marked by the Meckering Fault Line, Zone of rejuvenated drainage Upper middle Catchment and the Darling Range (Lower-middle Catchment) and west of the Darling Fault and scarp the Donnybrook Sunklands (Lower Catchment). Acknowledgement Figure 3 De Silva *et al*. 2000 modified in Kelsey 2002, courtesy DoW.



(a) (b)

Map 2.3 (a) Geology of Blackwood and Capes region showing the major fault lines **(b)** Surface hydrogeology.
Source DoW South West groundwater allocation Plan 2009 (a) Appendix Figure A6 (b) Figure 3. Courtesy T. Cattlin DoW.

Perth Basin

The lower reaches of the Blackwood and Scott rivers lie within the Perth Basin, a 1000 km long trough of sediments bounded on the east by the Darling Fault, which extends from the Shark Bay-Murchison area to the south coast. Twelve thousand metres of sediment have been deposited in layers over millions of years. Sands, gravels, sandstones, clays, silts, shales, coal and basalt reflect conditions at the time of formation and later processes such as compaction, heating and weathering. As a result the different layers or formations vary in the ability to impede water flow (aquitards) or to hold water (aquifers) (DoW 2009).

South of Geographe Bay, the Perth Basin consists of two geological units: the Vasse Shelf to the west where the Hardy Inlet lies, and the Bunbury Trough to the east, separated by the Busselton Fault (Map 2.3). The fault lines developed during rifting associated with the separation of south-western Australia from the super continent of Gondwana during the early Cretaceous 136 million years ago.

The Dunsborough Fault marks the boundary with the Leeuwin-Naturaliste Ridge and passes along the eastern margin of the Hardy Inlet. Other north-south trending faults, including the Darradup, also lie within the Bunbury Trough. These faults disrupt the continuity of the sediment layers, the interconnection between different aquifers, and ultimately water movements and greatly influence the hydrogeology. In addition some layers are missing due to erosion. For example, in the Scott Coastal Plain, west of Black Point, the Leederville Formation (consisting of the Vasse and Mowen members) lies beneath the Surface or Superficial Formation but in most of the eastern area this formation is absent, and the Yarragadee Formation lies immediately below the Superficial Formation. To add to the complexity, the Bunbury Basalt, extruded in its molten state along the fault lines formed during the break up of Gondwana, flowed across old drainage lines and the eroded surface of the Yarragadee Formation, creating an impermeable surface before other sediments were laid down.

2.3 Hydrogeology — Aquifers: Layers upon layers

Rainfall to the land surface accounts for most of the water passing through the rivers to the estuary. The amount that reaches the estuary, when it does so, and its constituents (such as salt), all depend upon the water's passage through the different soils, sediments and vegetation in the catchment.

Water in the Blackwood and Scott catchments is stored in the Superficial, Leederville, Yarragadee, Lesueur Sandstone, Sue Coal Measures, Cattamarra Coal Measures and Fractured Rock aquifers (Map 2.3 and Figure 2.4) (DoW 2009). While groundwater in the Superficial Formation has direct influence on surface and river flows, water in the other aquifers can also affect storage and water passage to the rivers, with the Bunbury Basalt and Parmelia Formation in particular forming barriers to water flow.

Recharge to the Yarragadee is influenced by rainfall through outcrops under the Blackwood Plateau and on the Scott Coastal Plain, with some contribution from rivers during high flows, and from other overlying aquifers. The Yarragadee Formation formed in the Middle Jurassic (176–161 million years ago) and the Leederville Formation of the Warnbro Group in the Early Cretaceous (146–100 million years ago). In addition to direct flow to the Hardy estuary, groundwater contributions to river pools in summer have a direct effect on freshwater habitats and communities of fish and macroinvertebrates (Morgan and Beatty 2005), which are indicators of river health.

Composition of the underlying geological structures dictates the capacity of water to accumulate between sediment particles (i.e. in the pores) and thus the storage capacity of an aquifer. Although storage volumes can be huge, small changes in water level at the watertable, or in confined aquifers measured as a pressure head, can severely affect surface features such as wetlands, swamps, rivers, estuaries and associated plant and animal communities, as well as pumping efficiencies and costs in bore fields. However, for changes in water level to occur, the aquifers need to be connected and have no confining layer inhibiting flow between aquifers. For example, the sandy areas of the Superficial and the underlying sandy Yarragadee are directly connected, therefore pumping Yarragadee can draw down the connected Superficial Aquifer. In coastal areas, high extraction rates also affect the interface of groundwater and seawater leading to contamination of groundwater with saline water.

The specific contributions of the aquifers are described below. The overall contributions of rainfall and aquifers to river flows in the Blackwood and Scott rivers are summarised in Section 2.5.

Superficial Aquifer

The Superficial Aquifer is formed by the uppermost superficial sediments of the Swan and Scott coastal plains (the Yoganup, Guildford Clay, and Bassendean sands, Tamala Limestone and Safety Bay Sands), which were deposited during the last 130,000 years. Water yields vary greatly depending on the type of material and the season, with a maximum in winter when recharged by rainfall and a minimum in summer. Localised saturated areas of groundwater in the Superficial Aquifer are underlain by the impermeable beds of the Leederville (Mowen aquitard), Yarragadee Aquifer, basalt or granite.

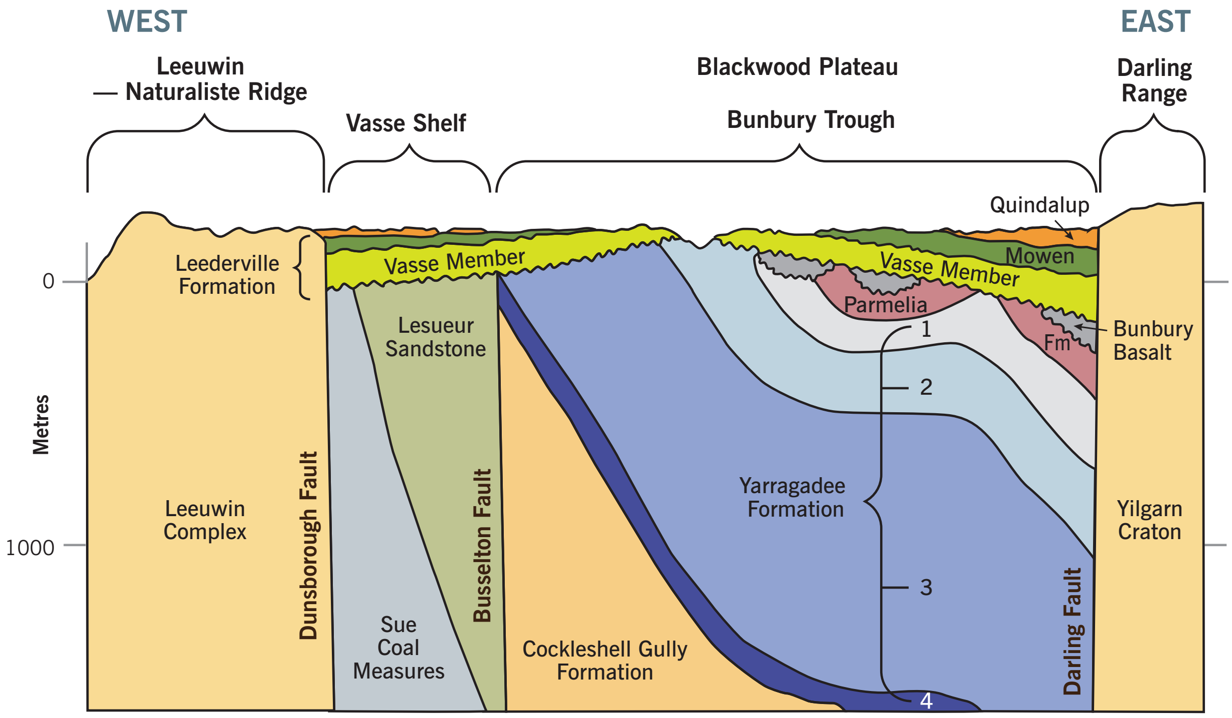


Figure 2.4 Conceptual geological cross section of the Southern Perth Basin. DoW South West groundwater areas allocation Plan 2009. Redrawn from Figure 2 supplied by T Cattlin DoW.

Leederville Aquifer

The Leederville Formation underlies the Superficial Formation and overlies the reworked Lesueur Sandstone and the Yarragadee Formation, although some outcrops of cemented iron sandstone and conglomerate are found on the riverbed and banks of the Blackwood River. The formation (Vasse, Mowan and Quindalup members), mostly 100m thick but in places 200m, consists of intermingled layers of sandstone and siltstone with smaller amounts of conglomerate, coal, or lignite deposited in rivers and marine environments during the Cretaceous. The Leederville, although classified as a confined aquifer, is recharged on the Blackwood Plateau by rainfall, on the coastal plain by downward leakage from the sandy superficial sediments, and upwards from the underlying Yarragadee. The watertable, 10–30 m below ground level, generally follows topography on the plateau. Lateral flow across the aquifer generally follows sand units. As it is shallow, easily accessed and generally fresh, the Leederville Aquifer is widely used on the Swan Coastal Plain. In the last 20 years there has been a decline of one to two metres in summer water levels and a decline in winter levels. Most of the decline occurred from 2003–2008 (a period of low rainfall), however some of the decline may have resulted from increased use, particularly in the Jindong agricultural area in the Buayanup River catchment south of Vasse. In 2008, the major uses of the Leederville Aquifer was for horticulture (23%), public water supply (20%), and pasture production (16%) (Department of Water 2009).

The Leederville Aquifer discharges into the lower Blackwood River between Nannup and Milyeannup Brook and downstream of Layman Brook, supplying base flow to the river. St John and Rosa brooks and upper Margaret River are Leederville dependent (DoW 2009).

Yarragadee Aquifer

The Yarragadee Formation, parts of the overlying Parmelia Formation and underlying Lesueur Sandstone and Cockleshell Gully Formations contain fresh water and form part of a major confined aquifer now commonly termed the Yarragadee. Some of the water is very old, 14,210 to 11,600 years. Some even older water (22,000 years) may enter from older formations below. The shallow areas have been aged at 3790 years, however as the water level in the aquifer fluctuates seasonally some water is much younger.

The Yarragadee is confined except in the south-eastern end of the Blackwood Plateau. It is recharged directly from rainfall in a 120 km^2 area where it outcrops, and by downward leakage from the overlying superficial formation on the coastal plain and from the Leederville Formation. The estimated recharge is about 200 mm per year in outcrop areas, and 100 mm per year where it is overlain by superficial formations, although there is probably no infiltration from the Parmelia Formation. Some groundwater also enters across the Busselton Fault from the Lesueur Sandstone on the Vasse Shelf. Discharge from the formation enters the Blackwood River and the Southern Ocean (near Black Point), with other ocean discharge through overlying formations, and possibly via the Donnelly River. The results of current investigations of the Yarragadee inflows and recharge, outflows and water usage have not as yet been released for public comment.

As the Yarragadee is the major fresh water aquifer in the south west, the Water Corporation has proposed abstraction of 45 GL/yr for the Integrated Water Supply Scheme, which provides water for Perth, the Wheatbelt, some South West towns and the Goldfields. Interest in the Yarragadee Aquifer extends back many years with the water first used to supply Bunbury in 1898. Mapping of the aquifer during explorations for oil in the 1960s stimulated development of supplies for Capel, Eaton and Busselton, and further investigation from 1967–1992 along the ‘Quindalup Line’ between Dunsborough and Busselton. Other deep drilling lines at Picton, Boyanup, Cowaramup and Karridale and shallow groundwater investigations over the coastal plains followed. The water resources discovered led to proposals to extend the Integrated Water Supply and programs to provide more detailed information on the aquifer (primarily the Yarragadee) structure.

While the Yarragadee Formation is present over much of the Perth Basin, outcropping near Mingenew in the mid-west more than 500 km to the north, in the context of the Blackwood and Scott rivers the formation extends for about 150 km north of the south coast and is about 40 km wide with a maximum thickness of 1200 m (Playford *et al*. 1975). The aquifer has several sub-units, each with distinct lithological (physical characteristics of minerals and grain size) and hydraulic properties. The main component is the predominantly sandy unit with a maximum thickness of about 800 m. Bores in this aquifer are capable of large yields of up to 600 to 20,000 KL/day. However, in some areas of the Yarragadee, water level has declined up to two metres over the last ten years. In 2008, the Department of Water (DoW 2009) reported that the major water use of the Yarragadee was for public supply (38%), mining (19%), horticulture (18%), and pasture production (15%). In this fastest-developing area of the State, use of all groundwater resources is expected to increase markedly, as are conflicting demands for this finite commodity (See also Section 2.5).

In terms of the Hardy Inlet, freshwater discharge from the Yarragadee enters the Blackwood River and its tributaries Milyeannup Brook and Poison Gully, maintaining perennial flow in summer, permanent pools and water quality. Many rivers on the coastal plains such as the Scott and Capel are also supported by groundwater.

Other aquifers

The smaller aquifers Cattamarra Coal Measures, Lesueur Sandstone, Sue Coal Measures and the fractured rock aquifer also contribute to water resources.

The **Cattamarra Coal Measures**, part of the Cockleshell Gully Formation, is a regionally confined aquifer composed of layers of siltstone and shale, inter-bedded with sandstone. Salinity (as total dissolved solids) ranges from 250–26,000 mg/L. To the north near the Kemerton Industrial Park and Bunbury the water is generally brackish. In the south salinity is generally lower, possibly due to inflow from the underlying Yarragadee Aquifer.

The **Lesueur Sandstone Aquifer** is present throughout most of the southern Perth Basin except for areas on the Vasse Shelf in the north and east of Augusta (Water Corporation 2005b, south west Yarragadee). Water is extracted only on the Vasse Shelf where it is overlain by the Leederville and Superficial formations. It outcrops east of Alexandra Bridge on the Brockman Highway and other outcrops may occur near the Scott River. Further drilling investigations of the aquifer have been conducted since 2009.

The **Sue Coal Measures** is deeply buried in the Bunbury Trough under the Leederville or Superficial formations on the Vasse Shelf and there are no outcrops at ground level. The formation consists of deeply faulted, consolidated and partially-cemented sandstone of generally low permeability and localised coarser, less-cemented layers. These characteristics affect the abstraction of water, however the limited data indicate that water levels are steady.

The **Fractured Rock Aquifer** consists of groundwater in the cracks of crystalline bedrock of the Leeuwin Complex and in the overlying weathered material and surface dune deposits. Caves and smaller cavities in the Tamala Limestone that overlies the bedrock facilitate rapid drainage of surface waters and underground streams, which can be seen discharging as springs along the coast at the interface of the older bedrock and younger sediments. Because of the complexity of the aquifer, little is known about the water levels, recharge areas or current use.

Aquifer use

Over 150 GL/yr of groundwater is already used in the South West Groundwater Area by licensed commercial and water supply operations. There are also smaller scale unlicensed abstractions for domestic and stock use from the 'water table' aquifer (i.e. the low-lying areas which are seasonal or permanent surface expressions of the water table). Water use across the whole area and from all aquifers is public water supply (24%), horticulture (27%), pasture production (15%) and mining (14%) (DoW 2009).

It is not known how the competing demands for water will impact the environmental flows in the Blackwood.

2.4 Major issues in the catchments

Clearing of the native vegetation, construction of drains, changes in water flows and significant development have initiated other changes, such as salinity, activation of oxidised acid sulfate soils and nutrient leaching. These issues are of increasing importance as they affect current and future use of the land and the estuaries downstream.

Salinity

In the Blackwood catchment, where 85% of the original vegetation has been removed, salinity in the streams increased from 500 mg/L in the 1950s to 2000 mg/L in the late 1990s.

Salinity of water stored in the aquifers varies greatly, being fresher in the recharge areas and in the deeper Leederville and Yarragadee aquifers, although these too have some areas of brackish (slightly salty) water.

Lake Dumbleyung, a dry salt bed in summer, January 2008. A. Brearley.

Origins of a salty landscape

In this old landscape of Western Australia, the soils contain salt deposited with rainfall, concentrated over the millennia by heat-driven evaporation and evapotranspiration by plants.

Removal of the deep-rooted native vegetation reduced water loss from the soil profile through transpiration, leading to a rise of the groundwater table and the increase and mobilisation of the salt stores.

Across the South West, 18 million ha of the original 25 million ha have been cleared. About 10% of this cleared country is salt-affected to some extent, with the projection that 8.8 million ha or 33% of the shallow water tables will be affected by salinity by 2050 (State Salinity Council 2000).

In general, groundwater salinity increases as salts are concentrated by evaporation and evapotranspiration by plants as the groundwater flows toward the coast. However salinity of the shallow (watertable) groundwater is also increasing in cultivated areas due to fertiliser use, with the salts recirculating from aquifer to soil and through to the aquifer.

Removal of groundwater can also lead to salinity issues through the disruption of the marine-freshwater boundary, which in the Superficial Aquifer on the Swan Coastal Plain can extend as much as one kilometre inland. As fresh water is removed the saline water can migrate further inland under the lighter out-flowing fresh water. When groundwater becomes brackish, it is no longer suitable for many uses and can severely affect deep-rooted vegetation.

This type of change is now evident along the coast and around a number of estuaries, such as the Peel-Harvey and lakes Clifton and Preston where trees have died.

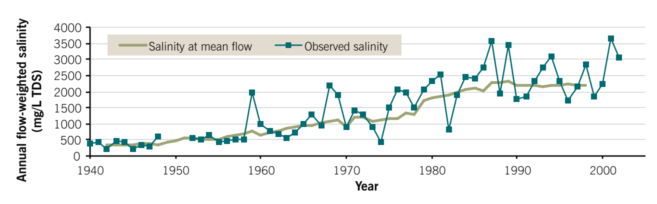
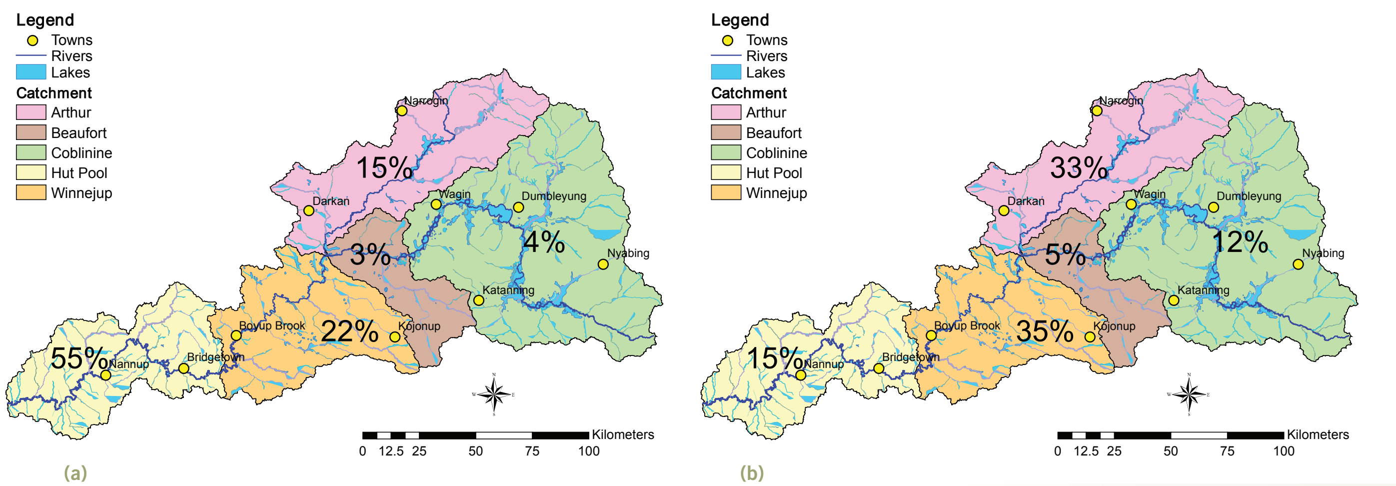


Figure 2.5 Salinity changes in the Lower Blackwood River (Darradup) 1940s to 2002. From Mayer *et al*. 2005. Courtesy DoW.



Map 2.4 Major subcatchments of the Blackwood are extensive spanning different soils, rainfall and landuse, which can grouped into 18 minor subcatchments. Percentage of flow **(a)** and salt **(b)** attributable to each of the subcatchments. Courtesy P. Kelsey DoW based on data from Ali *et al*. 2012.

Saline water also intersects the Leederville Aquifer at various depths along the coastline of Geographe Bay and the Yarragadee Aquifer near the coast at Bunbury, where it directly underlies the Superficial Aquifer. At Busselton, where the natural potentiometric head in the Yarragadee Aquifer is 15 m above sea level, fresh groundwater beneath the seabed is inferred to extend many kilometres offshore.

Net abstraction of water from the deeper aquifers is less likely to facilitate intrusions of marine water. However, connectivity between the different aquifers indicates that water levels, pressure heads and salinity throughout the South West need to be monitored with great care.

The annual salt load to the Hardy Inlet is currently estimated to be 693,000 tonnes each year. Salinity is a major feature of the groundwater in the upper catchments, with 33% of the load derived from the extensively-cleared Arthur catchment, 12% from the Beaufort and 40% from Upper Blackwood River (Map 2.4b). Only 15% of the salt is sourced from the Lower Catchment where the higher rainfall and groundwater flows from the Yarragadee and Leederville aquifers are fresh (300 mg/L) diluting the salt, a feature particularly evident in summer. In winter however, salinity in the river can be much higher as salt is flushed from the dry soils adding to the saline water from the upper catchment.

In 1978 Hodgkin suggested that rising salinity was unlikely to have major effects on the estuarine biota as rainfall in the area downstream of Nannup diluted the salts and a freshwater fauna flourished in some areas. This statement no longer applies. Decreased rainfall and increased water extraction are affecting the salinity regimes downstream and have changed the freshwater flush, which removed saline water and diluted nutrient and effects to biota could be substantial.

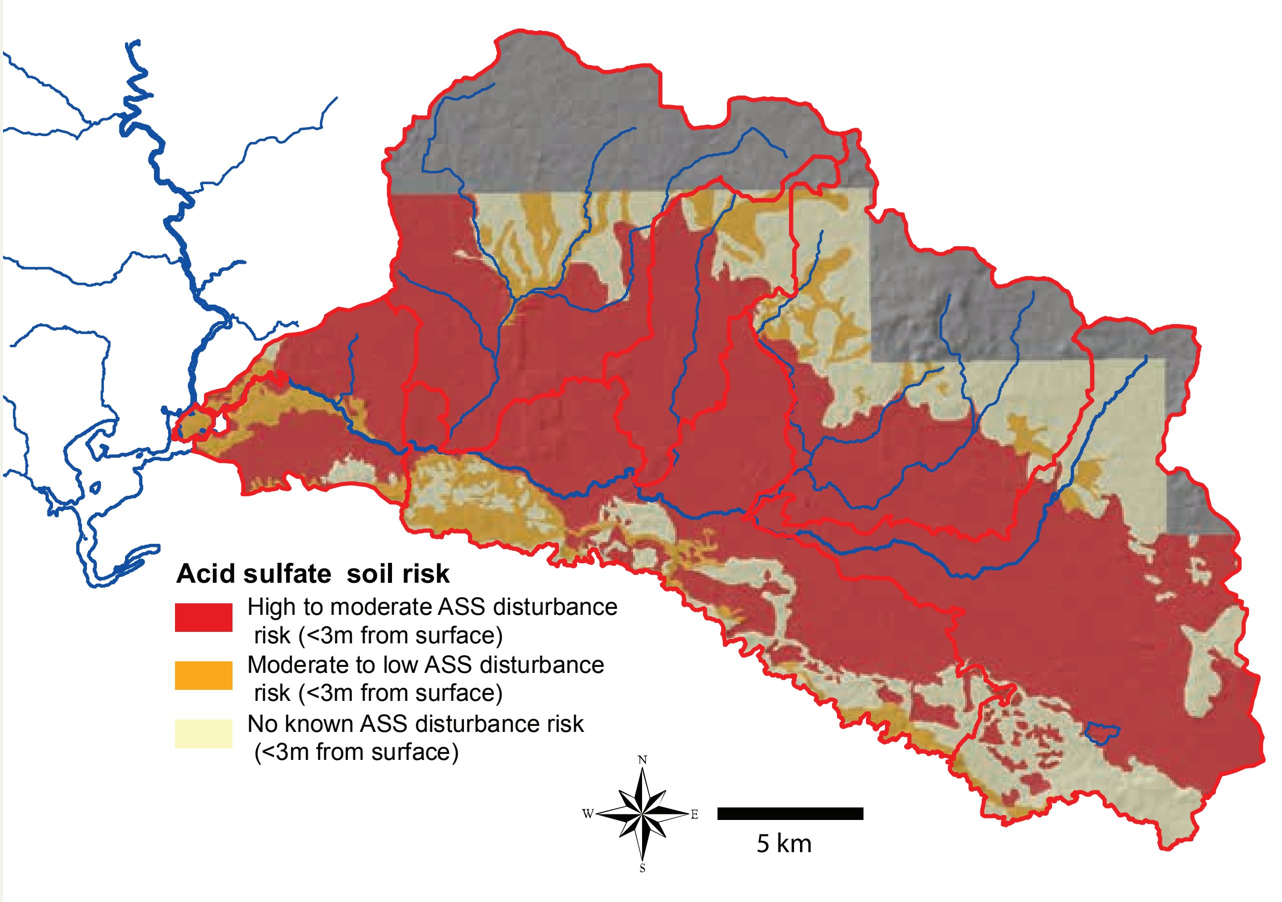
Acid sulfate soils

Areas with poorly drained soils like those on the Scott Coastal Plain are now recognised as likely to contain acid sulfate soils (ASS) (Map 2.5) (Degens and Wallace-Bell 2009; Kilminster 2009; Miller *et al*. 2010). Acidity is already evident in the area, visible as orange iron staining from bore water and in slowly flowing watercourses and swamps. As acidity of soils affects nutrient availability for plant and animal growth, mobilises toxic metals, may increase the toxicity of aluminium, and corrodes structures, the consequences to farm production and the environment could be substantial. The issue of potential acidity is aggravated by the evidence that effects will not be limited to the area of disturbance, but like all issues with water, downstream environments and neighbourhoods will also be affected requiring a whole-landscape approach to management. The Beenup mine, which closed in 1999, has been the subject of extensive site remediation to reduce the flow of acidic groundwater, activated during mining of the pyrite-rich deposits, across the plain and to the Hardy Inlet.

Acid sulfate soils

Acid sulfate soils are naturally occurring soils containing sulfides, principally as pyrite (iron sulfide — FeS$_2$). If undisturbed, ASS are usually benign, but if exposed to oxygen in air or to compounds containing oxygen, such as nitrate (NO$_3^-$), they can oxidise forming sulfuric acid (H$_2$SO$_4$). In the undisturbed state they are defined as potential acid sulfate soils (PASS).

The potential for acidity problems following disturbance of organic rich soils around wetlands and estuaries has been recognised for a long time but until recently often ignored e.g. around Torbay (*SWANLAND* pg 429, Woodward 1917) and in other areas (Miller *et al*. 2010; Sommer & Horwitz 2009). Soil acidity is however of increasing concern throughout Western Australia due to the lowering of the watertable, through water extraction, landscape drainage and dewatering, or decreased rainfall.



Map 2.5 Soil acidity and sites of concern 2009. An estimated 35% of the Scott Coastal Plain is at risk of acidification.
See Kitsios & Kelsey 2009 and Figure 3.3 White 2012. Courtesy J Hall DoW.

Orange staining due to iron release after disturbance of acid sulfate soils, Jarrahwood, Vasse Highway. Courtesy B. Degens DoW.

Nutrient leaching

Soils of the Scott River Coastal Plain have little capacity to retain nutrients, particularly phosphorus. As a result, much of the phosphorus applied as fertilisers moves to the groundwater, the river tributaries and through to the Hardy where it promotes algal growth.

Implementation of the highly contentious Fertiliser Action Plan 2007, proposed by the Joint Government and Fertiliser Industry Working Party in 2007, is particularly relevant to the Scott Catchment. The plan recommended phasing out use of highly water-soluble phosphorus fertilisers (80–100% soluble) in environmentally sensitive areas of the South West and replacement with fertilisers of low solubility (40% or less). In the urban setting of the Swan-Canning a reduction in the phosphorus content to 1% in lawn fertilisers and 2.5% in garden fertilisers would decrease phosphorus application rates by 30%. Furthermore uptake by plants is likely to be higher (up to 10%) as the lower solubility phosphorus will be retained in the soil for longer.

Development of strategies through State National Regional Management NRM projects for more comprehensive soil testing, analysis and mapping and a system for calculating the interaction of soil acidity (pH) and plant uptake of nutrients will provide better assessment of required phosphorus applications.

Phosphorus

Soils in Western Australia have naturally low concentrations of nitrogen and phosphorus. For high crop production, fertilisers containing phosphorus and nitrogen are required.

Phosphorus in the soils may be incorporated into organic matter, bound to metals such as iron, aluminium or calcium, or dissolved in water. Dissolved phosphorus is readily available for plant growth. Organic phosphorus is 'readily' released as biological material decays. Inorganic phosphorus however provides a long-term resource as it can be released from the binding material in response to waterlogging, oxygen and pH changes.

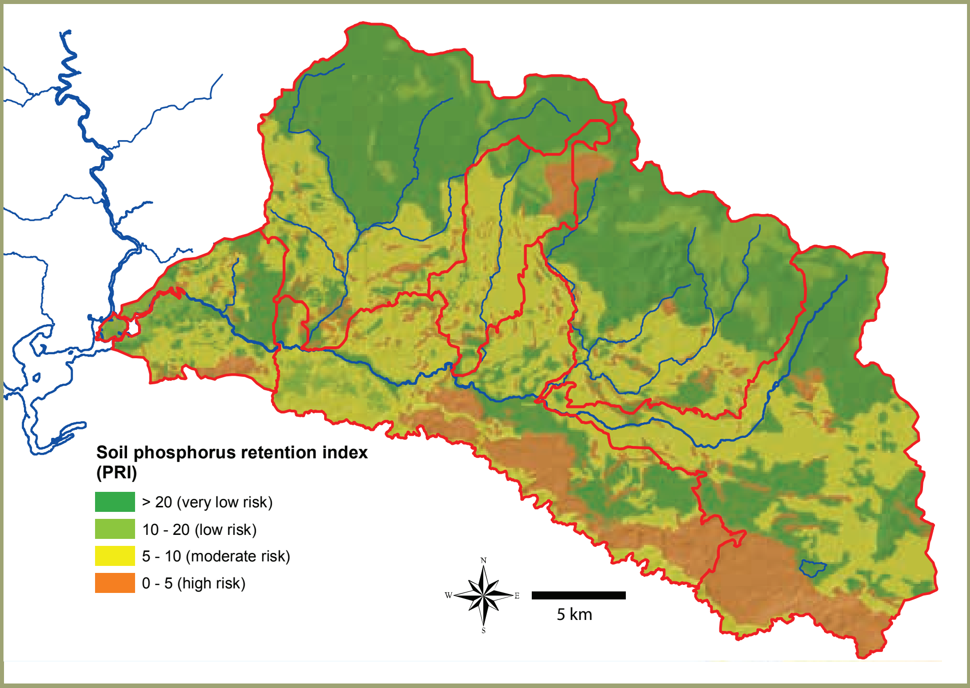
In many instances as the soil stores are already high phosphorus is applied in excess to growth requirements. With anticipated global rock phosphate shortages there is an increasing economic imperative to ensure that phosphorus is used more efficiently. Losses therefore can be viewed not only as a threat to water quality but as uneconomic.

Perhaps not surprisingly dissolved reactive phosphorus concentrations in 95% of the soil samples in south-west Western Australia exceed the ANZECC and ARMCANZ 2000 guideline standards (Weaver and Wong 2011). This recent analysis of the phosphorus balance across farming systems in southern Australia found that phosphorus applications exceeded critical values required for maximum production. In 50% of samples, other soil conditions (soil acidity, potassium and sulfur deficiency) were of greater importance for maintaining yields. Addressing these issues would improve the economic efficiency and environmental outcomes. In many cases the sulfur deficiency has been addressed by applying super phosphate, which contains phosphorus and sulfur, and the phosphorus component is not required or utilised by plants.

The Phosphorus Retention Index (PRI) developed by the Department of Agriculture of Western Australia (DAFWA) allows this issue to be viewed more clearly as an aid to management and is now used throughout the south west to identify other areas with this problem (Map 2.6). The index provides a method for examining:

- movement or transport of phosphorus within the landscape, due to rainfall and or irrigation, erosion and runoff;
- the amount and forms of phosphorus in the soils; and
- timing and methods of phosphorus application.

These factors are weighted according to a judgement regarding the influence of phosphorus movement through the sites, and rated from 'no effect' to 'very high', based on the current management. The assessment thus provides a framework for intervention to either soils or water to minimise applications and reduce transport of phosphorus and contamination of a receiving water body.



Map 2.6 Soil phosphorus retention index (Figure 2.6, Hall 2011) based on DAFWA mapping and soil assessments. (McPharlin *et. al*.1990). The PRI Index is related to soil type, depth of the two uppermost layers and fertiliser history. Areas of greatest concern are tributaries flowing southwards from the Barlee Scarp across four acres Road and Dennis Road.

2.5 River flows

Blackwood River

The Blackwood River brings an average annual flow of 478 GL to the Hardy Estuary. Flows from the subcatchments vary considerably, with only 7% derived from the Beaufort in the south-eastern section, 15% from the Arthur River in the north-east, 21% from the Upper Blackwood between Kojonup and Boyup Brook, and the greater volume of 57% derived from the Lower Blackwood in the higher rainfall forested areas (Map 2.4).

The lower Blackwood also receives water from the Chapman River (≈5%), near Warner Glen Bridge, and McLeod Creek and other smaller creeks, which flow through an area of vineyards and farmland south of Margaret River. Flow to the Hardy Inlet also enters from Turnerwood Creek via North Bay, from West Bay Creek, and from urban areas of Augusta.

River flow in the lower catchment is measured at two locations, Darradup and Hut Pool. The older upstream station at Darradup, 64 km upstream of Hut Pool, was established in 1956 but was not operational from 2000 to 2006. The Hut Pool station (near Great North Road and Carey's Flat), downstream of the Yarragadee discharge areas and approximately 43 km upstream from the Hardy Inlet, was established in 1983 (Figure 2.6 and 3.1). The two gauging stations allow the contribution of rainfall in different areas of the catchment and from aquifer recharge to be quantified.

While winter flow responds primarily to rainfall runoff, summer base flow is influenced by groundwater from aquifers including the Leederville and Yarragadee Formations. In March 2003, when there was no precipitation, estimates of flow from the Yarragadee, based on streamflow and length of outcrop (about 15 km), were 11.5 GL/year. Inflow to the whole length (64 km) of river between the gauging stations was 20.5 GL/year. The contribution from the Yarragadee is therefore about 56% of total base flow. The 20.5 GL was higher than the longer-term average of 11.5 GL/year from the gauging stations, illustrating the seasonal variability in flow (MacHunter and Vogwill 2004).

The river flow during the 1974 study was 1437 GL, which is among the highest on record. The only years in which is was exceeded were 1955 (1159 GL), 1963 (2039 GL), and 1964 (1782 GL).

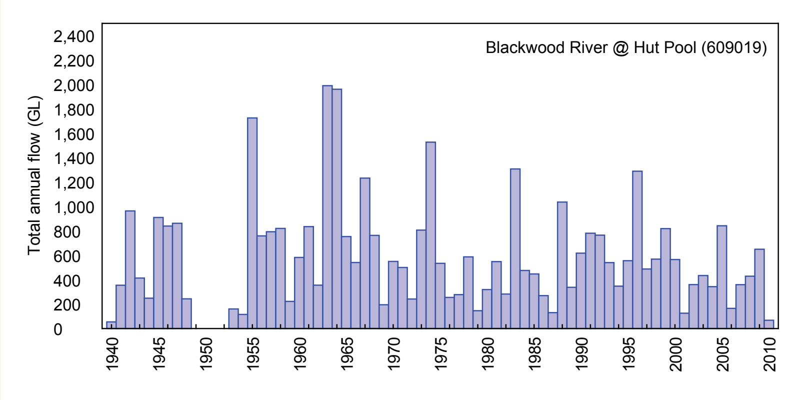


Figure 2.6 Blackwood River flow to the Hardy Inlet 1940–2010 estimated at Hut Pool approximately 43 km upstream from the Hardy Inlet. Prior to the establishment of the gauging station at Darradup, flow was based on records from the Nannup station, which was operational in 1940. Recently another gauge, White Elephant, was installed at the confluence of Chapman Brook and the Blackwood River. Courtesy K. Kilminster, DoW.

The floods in August 1964 reached the roadway at Alexandra Bridge and were over the handrails of Warner Glen Bridge, about nine metres above normal level (Hodgkin 1978). At Darradup the flow rate on 8 August 1964 was 969 m^3/sec.

Although the rainfall in 1974 was regarded as only average, winter river flow was high, partly because early rains saturated the ground and allowed maximum runoff from the July-August rainfall. Hodgkin (1978) noted that floods were also reported in 1955, 1945 and 1926. In the last 35 years only three flows, 1974 (1437 GL), 1983 (1148 GL) and 1996 (1210 GL), have exceeded 1000 GL, with the next largest flow of 871 GL in 1988. The most recent high flow was 842 GL in 2005 (recorded at the Hut Pool station). It is however notable that in 1988, 871 GL was measured at Darradup but 1036 GL at Hut Pool, illustrating the amount of runoff in that area.

With declining river flows due to water harvesting and low rainfall, changes in the contribution to base flow, particularly in summer, could have a profound effect on river and estuarine environments.

Scott River

The volume of water flowing from the Scott is small compared to the large Blackwood and accounts for approximately 15% of the flow to Hardy Inlet. The highest flow from the Scott occurred in 1973 and was estimated to be 197 GL. With the exception of 116 GL in 2000 and 123 GL in 2009, yearly flow in the last ten years has been less than 100 GL each year. Overall flow decreased 35% in the last decade (2000–2009) compared to the average for 1970–2000 of 94.7 GL.

Since 1969, flow has been measured at Brennan's Ford, about nine kilometres upstream of the river mouth. A further 12 km upstream at Milyeannup Bridge, flow was measured between 1996 and 1999. The gauging station at Brennan's Ford captures flow from 643 km^2, which is about 93% of the catchment. At Brennan's Ford approximately 50% of the flow is baseflow (i.e. from groundwater flow entering a watercourse). The remainder is predominantly surface runoff from low-lying waterlogged areas on the plain, with a smaller contribution from the heavy soils in the northern part of the catchment (Hall 2011). Drainage across the plain is now modified. Flows are classified as ephemeral and generally start in May or June and cease in November or December.

Runoff depends also on the area of hard surface, which in the case of the Scott is negligible, on the amount of water held in the soils and the type of land use, for example cleared and agricultural land compared to deep-rooted vegetation (native vegetation or plantations). Artificial drains that increase water movement and therefore the capacity to transport more nutrients have extensively modified catchment hydrology. Runoff from irrigated land is comparatively high because the soil is already saturated and does not require the initial rain for runoff to start. However the runoff and river flow relative to rainfall has decreased markedly (35%) in the last decade. (See also Section 2.7).

The decrease in river flow could be due to changes in land and aquifer use, which are as yet unstudied in the Scott catchment. Such changes include increased evapotranspiration associated with the expansion of blue gum plantations. These utilise the unsaturated zone, and influence groundwater recharge and levels, runoff and baseflow discharge. Another factor might be increased use of the Yarragadee Aquifer and its effects on the overlying Superficial Aquifer in some parts of the catchment. The effects are compounded by climatic changes such as the timing of rainfall and higher temperatures that influence evapotranspiration rates.

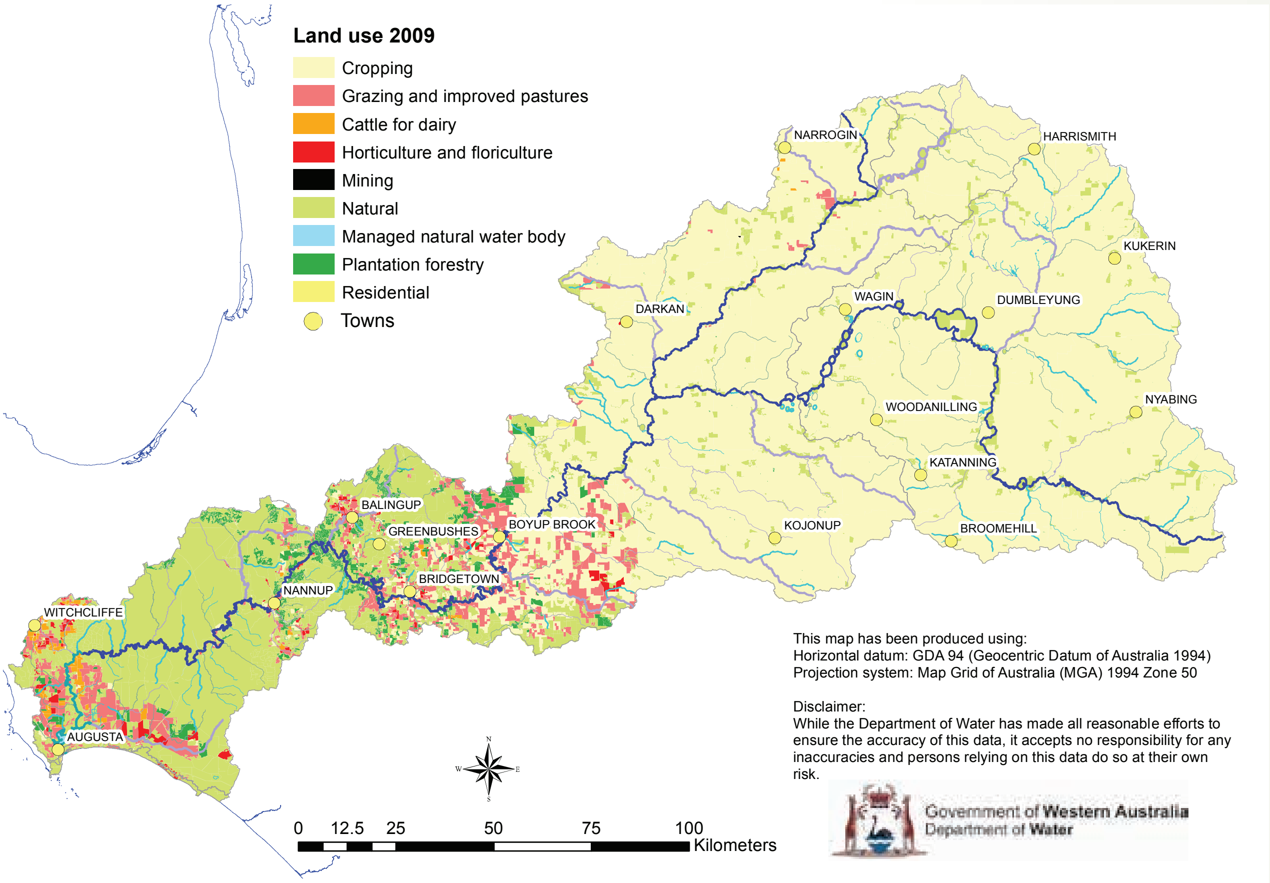
The waters flowing from the Blackwood and Scott systems are also different. The water from the Scott is characteristically tea-coloured due to humic acid from the ironstone deposits and tannins (fluvic acid) released during decay of leaves of native vegetation including tea trees, paperbarks (*Melaleuca*). Nutrient concentrations are higher due to intensive agriculture in the Scott catchment.

2.6 Vegetation, land use and nutrients — Blackwood catchment

The upper catchments of the Arthur and Beaufort, now largely cleared of native vegetation (eucalypt woodlands and woody shrubs), are used predominantly for broad-scale cropping, sheep and some cattle production. Small towns are widely dispersed.

Downstream to the south and west where soils are more fertile and rainfall is higher and more reliable, clearing is less extensive. Large areas of eucalypts (karri, jarrah and marri with shrubby understorey) have been reserved for national parks, conservation, timber production and water reserves. However stocking densities are higher due to fertiliser applications and improved pastures of nitrogen-fixing clovers. Large areas are also used for plantation timbers, which now supplement logging in forest and conservation areas.

More intensive horticulture with orchards, vineyards, and intensive grazing of dairying and beef cattle is conducted in the higher rainfall areas downstream of Boyup Brook, Bridgetown, Balingup and Nannup in the Lower-middle Catchment, in the west around Witchcliffe and the area around the main Blackwood channel, and eastwards around the Scott River (Map 2.7) (Kelsey 2002).



This map has been produced using:
Horizontal datum: GDA 94 (Geocentric Datum of Australia 1994)
Projection system: Map Grid of Australia (MGA) 1994 Zone 50

Disclaimer:
While the Department of Water has made all reasonable efforts to ensure the accuracy of this data, it accepts no responsibility for any inaccuracies and persons relying on this data do so at their own risk.

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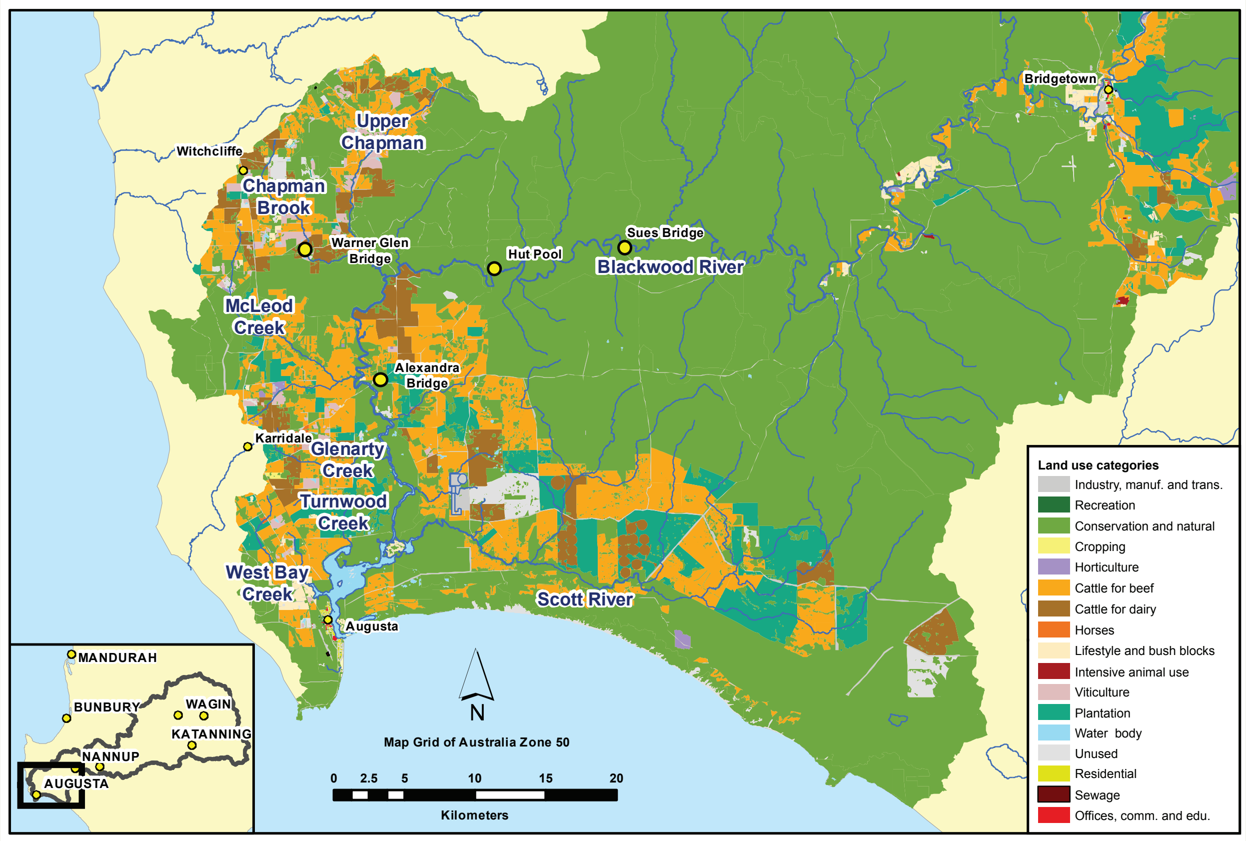
Map 2.7 Land use in the Blackwood and Scott River Catchments 2005–2007. Based on Kelsey 2002. Courtesy P. Kelsey DoW 2012.

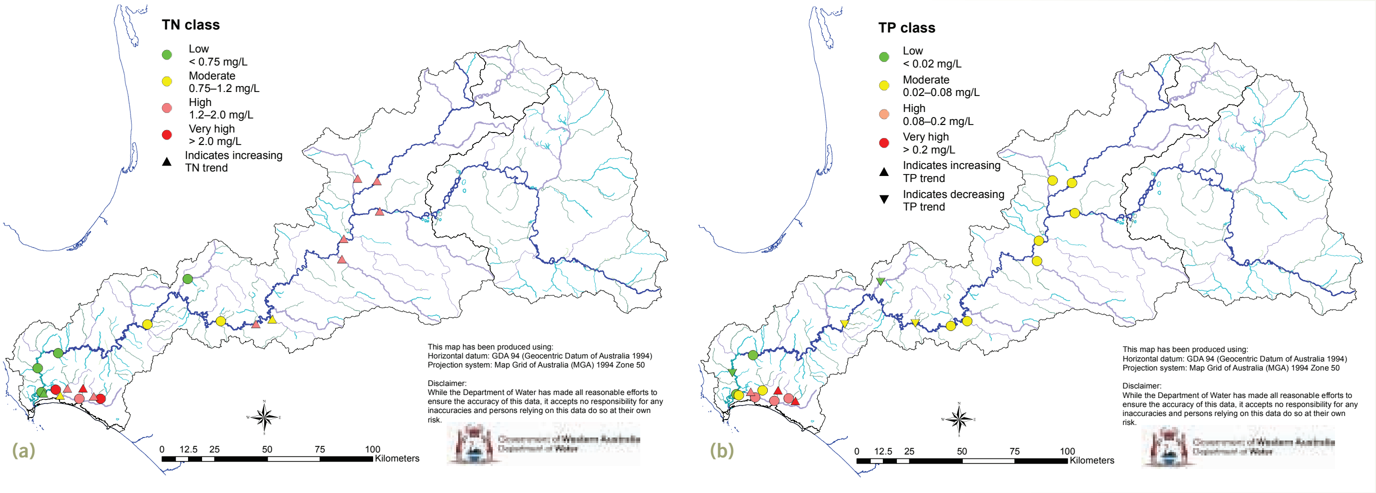


Map 2.8 Land use in the ten subcatchment of the Lower Blackwood. Courtesy B. Marillier DoW 2011.

Recent mapping of land use across the entire Blackwood and Scott catchment (Marillier 2011) indicates that cropping accounts for the largest area — 57% of the 20,000 km^2 basin. The next major category was 'unused areas' and covered 26% of the catchment, 22% of which was uncleared with trees and shrubs, with smaller areas of 'inundated' cleared and vegetated saline land. Mixed grazing occupied 5% of the catchment, recreation areas for conservation with trees and shrubs 4%, hardwood tree plantations 3%, and transport and water bodies 1% each.

In the lower Blackwood catchment where agriculture is most intense, the most recent synthesis of activities (Map 2.8) by the Department of Water (Water Science Branch) in the ten subcatchments downstream of Nannup indicates that over 60% of the 827 km^2 is occupied by trees and shrubs, for recreation, conservation (27%) or uncleared and unused (37%). Mixed grazing covers 152 km^2 (18%) and dairy cattle 57 km^2 (7%) of the land. In the area surrounding the estuarine reaches, grazing occupies 46 km^2 (30%).

Cropping and sheep grazing near Kojonup. Courtesy M. Hele



Map 2.9 Summaries and trends **(a)** Total Nitrogen (TN) and **(b)** Total Phosphorus (TP) in rivers flowing from the Blackwood and Scott River to the Hardy Inlet. Section 2.7 for detailed maps of the Scott River. Source DoW. Courtesy P. Kelsey.

Throughout the catchment, changes in land use and intensity have been possible only with substantial changes in agricultural practice, including development of minimal tillage and increased applications of fertilisers to old infertile soils. This history of adding nutrients has gradually increased the amount of nutrients moving into the groundwater and through to river waters and sediments. In general, comparing the maps of land use and nutrients (Maps 2.7 and 2.8) indicates that nutrient concentrations in the Blackwood in 2005–2007 were higher in areas with more intense agriculture, although in the higher-rainfall part of the lower Blackwood, concentrations of total nitrogen (TN) and total phosphorus (TP) were low. Total nitrogen concentrations were high and increasing at stations in Lower Arthur and Beaufort and moderate to high in waters between Boyup Brook and Bridgetown, but were low downstream of the forest country traversed by the Brockman Highway (Map 2.9a).

Total phosphorus followed a similar pattern to TN with moderate concentrations at sites in the Arthur and Beaufort catchments and moderate in upper Blackwood (Map 2.9b). Concentrations of oxygen were particularly low in the Blackwood main channel where TN and TP were moderate or high. Water acidity (pH) was neutral throughout most of the sub-catchments. However acidic conditions were recorded in the upper Beaufort north of Lake Dumbleyung.

In terms of nutrient loads that enter the Hardy Estuary, the Blackwood contributes an average of approximately 344 tonnes of TN and 6.2 tonnes of TP each year. Although these amounts are large, the Blackwood catchment is 30 times larger that the Scott and flow seven times higher, but TN is only 4.5 times greater. The contribution of TP from the Scott is twice as high as the Blackwood (White 2012).

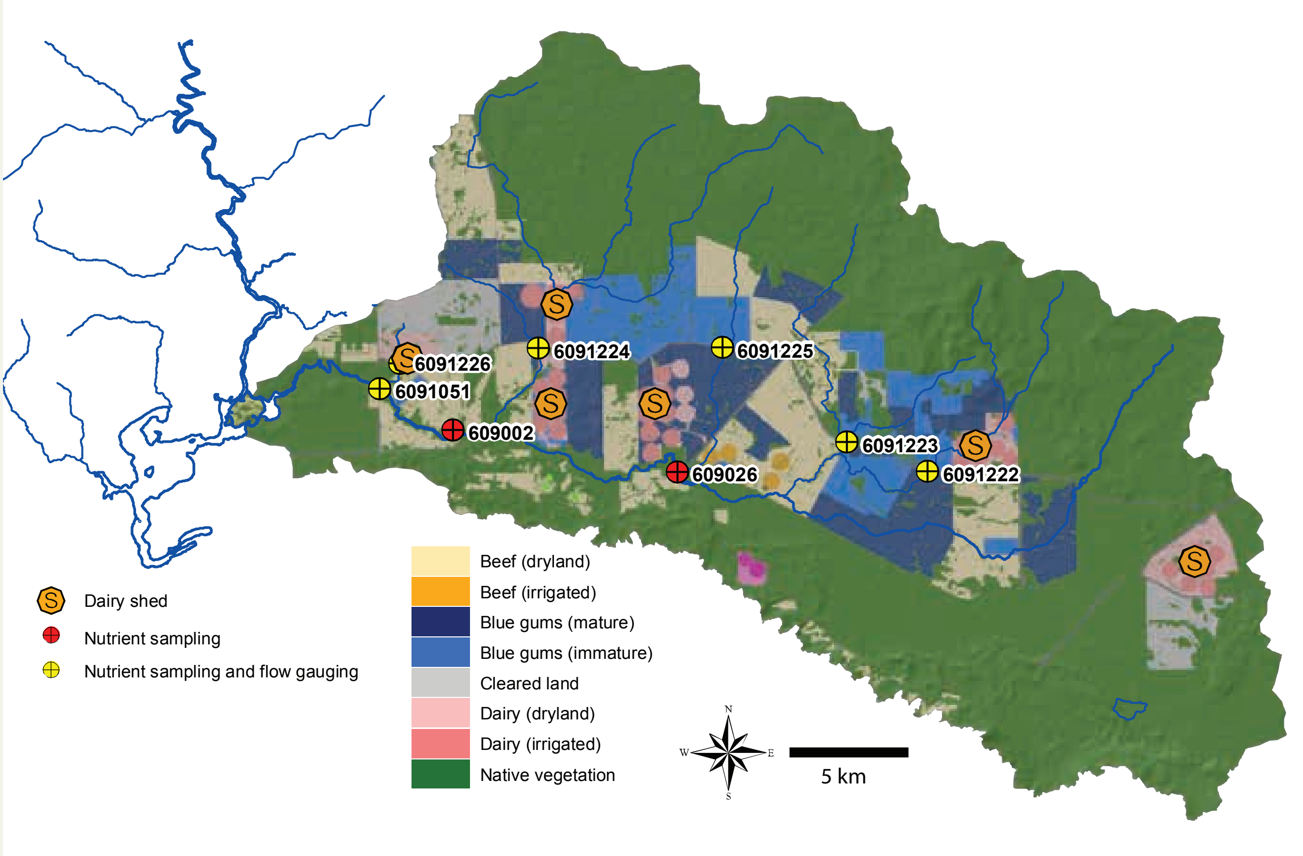
2.7 Vegetation, land use and nutrients — Scott catchment

The Scott Coastal Plain is of considerable botanical interest. It has a number of endemic species and is the western boundary of some south coast species (Gibson *et al*. 2000; Luu and English 2004). Although the area was grazed in the 1800s and early 1900s, clearing of native vegetation was limited until the 1970s. Native vegetation still covers almost 70% of the catchment, however much of this is in the northern area of the Donnybrook Sunklands and a much greater proportion of the Coastal Plain has been cleared. Remnant vegetation consists of woodlands of peppermint trees (*Agonis*) near the coast, paperbarks, reed swamps, sedges and heaths in wetter areas, and jarrah-marri on drier upland areas. Fringing or riparian vegetation still borders the main Scott River channel where a foreshore reserve was established at the time of title allocations.

The low-lying areas along the Scott River were developed for agriculture in the 1970s but the type and intensity of land use has changed considerably over the years (Map 2.10, also 2.5 and 2.6).

Access to abundant water supplies in the mid 1990s allowed the development of a potato industry but closure of the processing facility in Manjimup in 1999 meant this was no longer economical, and many properties converted to dairy cattle (Kitsios and Kelsey 2009). The area is highly productive with about 11% of the area currently used for dry-land beef grazing, 4% for dairy cattle and 14% for tree farming.

Fertiliser applications required for maintaining production in the naturally poor soils vary considerably: potatoes require large applications of phosphorus, dairy cattle need nitrogen-rich fodder either from fertilised pastures or nitrogen-fixing legumes in pastures, and newly-established tree plantations also require fertilisers. In the period 2000–2007, there was a 9% increase use in the use of nitrogen and a 20% decrease in phosphorus applications across the catchment (Kitsios and Kelsey 2009) (Section 2.4 Nutrient leaching).



Map 2.10 Land use in the Scott River Catchment 2010. Based on mapping by Department of Agriculture and Food (DAFWA) 2000 and updated after interviews by DAFWA and DoW staff, Blackwood Basin Group, Lower Blackwood Landcare and with landholders to document land use, stocking tillage and fertiliser rates, water storage and use. The western area is administered by the Shire of Augusta-Margaret River and eastern area by the Shire of Nannup. See Figure 8.2 Hall 2011 and Figure 3.8 White 2012. Courtesy J. Hall DoW.

Water quality

In recent years nutrients flowing from the Scott catchment to the Hardy were considered disproportionately high, particularly in comparison to the volume of river flow. Until 1999, water and nutrient monitoring was limited to one gauging station at Brennan's Ford. However with increasing concern about the elevated nutrients coming from the Scott, another flow gauge was installed at Milyeannup Bridge and seven new nutrient stations were added to the program in 1999. Samples were collected fortnightly when water is flowing, usually between May and November.

Sampling nutrients and detecting changes or trends in nutrient concentrations is difficult, and attributing what might be influencing changes even more complicated. We know that nutrient concentrations in soils and water vary with seasonal changes in flow, land use and management, timing of fertiliser applications (which often vary with rainfall), and with erosion in response to clearing, fires and floods. Although the changes induced by humans compound natural variations, the influence of flow and seasonal effects need to be clearly identified to clarify the impact of human activities.

Another complication in identifying change is the residence time or store of nutrients applied as fertilisers, fixed by bacteria, and from animal waste. Storage depends on the type of soils, groundwater and vegetation. Nutrients delivered to a watercourse occur in particulate and dissolved forms. Within a watercourse they may be precipitated, or adsorbed to sediments, taken up by vegetation in the channel or transported in river flow, with only a small proportion reaching an estuary, in this case the Hardy Inlet.

In assessment of nutrients in watercourses, the previous five to ten years are usually considered the most critical in the determination of immediate changes. However if we are interested in when conditions started to change even if the implications or expressions of these changes were not apparent, the longer historical data are useful.

Nutrient status 1984–2009

In 1984, TP concentrations in the Scott River measured at Brennan's Ford (about 8.5 km upstream beyond the estuarine influence) averaged 0.02 mg/L, but by 2008 had increased tenfold to 0.22 mg/L (Figure 2.7), well above the ANZECC 2000 guideline for lowland rivers of 0.065 Mg/L. Although concentrations of TN in the 1980s are unknown, with the earliest record of 0.64 mg/L recorded in 1991, the range of the 2008 concentrations illustrates that nitrogen had increased and was above the guideline for TN of 1.2 mg/L.

Concentrations of TN and TP in river water at the new sampling stations have also been high or very high at all sites, generally exceeding ANZECC 2000 guidelines except for TN at Brennan's Ford and TP and Coonack Downs. In 2007 median TN concentrations

Table 2.1 Nutrient status and medium nutrient concentrations Scott River catchment 2007–2009 (Table 3.2 Hall 2011). Courtesy DoW.

Site	AWRC reference	Site context	Median TN (2007–2009) mg/L	TN status	Median TP (2007–2009) mg/L	TP status
Brennan's Bridge	6091051	Bottom of the Scott River	1.00*	🔵	0.12*	🟡
Brennan's Ford	609002	Lower Scott River	1.00	🔵	0.15	🟡
Milyeannup Bridge	609026	Middle Scott River	1.40	🟡	0.18	🟡
Woodhouse	6091226	Scott River tributary	1.75	🟡	0.14	🟡
Coonack Downs	6091224	Scott River tributary	1.20	🔵	0.04	🔵
Governor Broome	6091225	Scott River tributary	1.60	🟡	0.15	🟡
Electric Fence – Four Acres	6091223	Scott River tributary	1.40	🟡	0.15	🟡
S-Bend	6091222	Scott River tributary	2.20	🔴	0.68	🔴

* median concentration for this site was for 2004–2006, as samples ceased being collected at this location in 2006.

Status		TN three year winter median concentration (mg/L)	TP three-year winter median concentration (mg/L)
Very high	🔴	> 2.0	> 0.2
High	🟡	1.2–2.0	0.08–0.2
Moderate	🔵	0.75–1.2	0.02–0.08
Low	⚫	< 0.75	< 0.02

had increased at all sites, while TP concentrations had increased at only three sites (S-Bend, Electric Fence – Four Acres and Milyeannup Coast Road). For the period 2003–2007, the increasing trend of TN was significant while the trend for TP was not significant.

Based on the three year period 2007–2009, which represents the recent input of nutrients (Table 2.1), TN was moderate to low in three of the eight sites and high to very high in the other five sites. Total phosphorus was high to very high at seven of the sites. Coonack Downs was the only site where TN and TP were low. The highest concentrations were at S-Bend, Milyeannup Bridge and Woodhouse. Brennan's Bridge and the ford located at the lower section of the Scott River below the higher tributaries had the lowest nutrients. This indicates that the thick vegetation may be assimilating nutrients or there is a dilution effect from northern streams i.e. Coonack and Dennis areas. However given the intensity of agriculture between the Brennan's area and Milyeannup, such dilution is unlikely.

Low oxygen concentrations have been recorded in Scott River sites but the relationships to nutrients are not clear. Acidic conditions have also been recorded at a few sites and very high aluminium concentrations reported in the western area, which may indicate release from soils under acid conditions. To date, the increase in nutrients in the Scott River has had little effect on the growth of algae, as the brown tannin-coloured water probably limits the light available for photosynthesis. Algal blooms do however occur in the estuary, particularly at the confluence of the Blackwood and Scott rivers around Molloy Island (See Chapter 4.1).

Given the evidence of elevated and increasing nutrients entering the waters of the Scott and flowing to Hardy Inlet, management options were assessed. This included mapping of the landforms and soils that contribute to acidity (Map 2.5) and phosphorus mobilisation (Map 2.6), and of land use (Map 2.10). Surveys of the amount and timing of fertiliser applications were collated during consultation with local government officials, landholders and government agencies (including the Department of Agriculture and Food and the Department of Water) in 2000, 2005, 2007 and 2009. These data, coupled with the data on water quality and flows, can now be used to develop strategies to reduce inputs in the longer term.

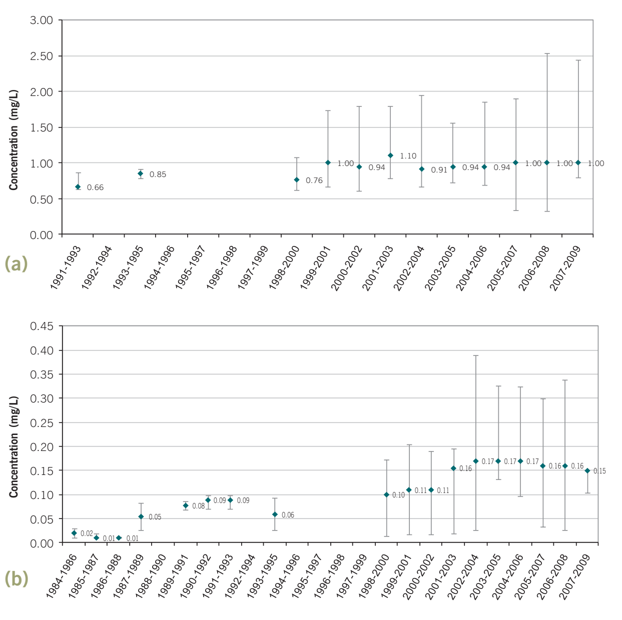


Figure 2.7 (a) Nitrogen and **(b)** phosphorus (median) in the Scott River at Brennan's Ford 90th and 100th percentiles. Phosphorus 1984–2009 and nitrogen 1991–2009. Figures A-5 phosphorus and A-6 nitrogen from Hall 2011 courtesy DoW.

Although water samples were not collected continuously, early samples were taken before agricultural activities intensified. There is an obvious increase in the TP concentrations in the latter period above ANZECC 2000 guidelines (0.065 mg/L) for lowland rivers in Western Australia.

Land use and fertiliser application in the Scott catchment

The high intensity of agriculture and productivity in the Scott catchment is due in part to the development of specifically designed fertilisers, which vary in the proportion of nitrogen and phosphorus and in the application rates and the frequency of application (Hall 2011). Nitrogen is also contributed by legumes, such as clover pastures and some bushland species (e.g. *Acacia*), which harbour nitrogen-fixing bacteria in their root nodules. Nutrients are also derived from faeces and urine of grazing stock and from fodder imported to supplement pasture. In general these nutrients can be described as diffuse as they are spread across the landscape. Not all of these are retained where they are applied. Some move through the soils to the streams and rivers. There are also some point sources, such as dairies and residential septic tanks, where nutrients may be more concentrated.

Rates of fertiliser application in the Scott catchment (Table 2.2) were based on surveys undertaken by the Department of Food and Agriculture Western Australia (DAFWA). Based on research at Vasse in the Geographe catchment and research by Peoples *et al*. (1994 and 1995), nitrogen fixation was assumed to contribute 150 kg N per ha each year in irrigated pasture and 75 kg/ha/year in Dryland pasture (Table 2.2).

Irrigated areas used for dairy cattle accounted for the largest input of nitrogen, more than five times that of dryland beef cattle, followed by irrigated horticulture, dryland dairy cattle and blue gum plantations. Dairying, dryland beef and immature blue gums contribute the highest loads per area. Loads from irrigated horticulture, irrigated beef, residential areas and seasonal horticulture were much lower.

Horticultural and irrigated dairy areas receive the largest input rates of phosphorus. However, further research indicated that the groundwater from the horticultural area flows towards the coast and does not contribute to the load entering the Scott River. The loads from the dryland beef area and the dairy cattle area were similar as the area used for beef production was five times higher than that used for dairy. The large area of newly planted blue gums contributed the third highest load.

The table does not include the nitrogen and phosphorus in fodder imported from other areas to supplement pastures. While the nutrient component was small, the fodder is concentrated into discrete areas while cows are milked.

Point sources

Investigations of effluent discharge were conducted at seven point sources — six dairy sheds and one feedlot. The effluent loads were calculated from the volume of discharge multiplied by the effluent concentrations of TN (230 mg/L) and TP (40 mg/L) (DoE 2004). Direct effluent discharge to the surface or to small ponds on sandy soils was assumed to be contributing all nutrients to the environment. Based on research at Vasse, 30%–60% reduction of nutrients was assumed when effluent was dispersed during irrigation or stored in partially sealed ponds, dependant on the number of ponds.

Similarly feedlots were assumed to export 8.66 kg nitrogen and 2.24 kg phosphorus per cow each year. Combined catchment inputs from point sources were estimated as 6.4 tonnes of nitrogen and 1.34 tonnes of phosphorus each year.

Septic tanks

The input of nutrients at Molloy Island was based on the number of established residences and the average annual rate per septic of 1.1 kg phosphorus and 5.5 kg nitrogen (Whelan and Burrow 1984). However as most houses on the island were not occupied on a regular basis, an average residency rate of one person per house was assumed. This gave an annual average input of only 0.22 tonnes of TP and 1.1 tonnes TN. More recent surveys (Jeffery 2010) indicate that nutrients also appear to be retained around the islands leach drains by the PRI soils and vegetation. Further studies to be conducted in 2012 are planned to substantiate the findings and retention processes (White 2012).

Modelling potential land use and water quality on the Scott Coastal Plain

Information on water quality and flows from the additional gauging stations, together with the detailed mapping, provided data that could be incorporated into modelling programs. Initially the 'Square' model was developed by DoW to simulate movement of water and nutrients across the surface and through the soil to water bodies (DoW 2007; Kitsios and Kelsey 2009). More recently a new model 'Source Catchments', developed by eWater (2005–2008) and designed for hydrologic and constituent modelling at whole-of-catchment scale, was found to be more appropriate for examining the Scott catchment (Hall 2011). Flexibility of this model allows for analysis of specific problems and the constraints of the data and knowledge.

Table 2.2 Fertiliser applications in the Scott Catchment 2000–2009 (Table 3.4 Hall 2011). Surveys identified twenty land use categories, which were combined into eight groups, which had the greatest nutrient inputs. Other land use but with lower nutrient input includes; Blue gums mature 58.9 km^2, cleared land 16.7 km^2, roads 8.6 km^2, horticulture irrigated 0.6 km^2, Residential 0.6 km^2, Lucerne 0.3 km^2. Fertilisers are formulated for specific crops with the amount and timing of applications dependant on the particular crop.

Land use	Fertiliser rate (kg/ha)		Fixation(kg/ha)	Total input rate (kg/ha)		Area (km^2)	Total input load (t/yr)	
	TP	TN	TN	TP	TN		TP	TPN
Dryland beef	19.8	39.9	75.0	19.8	114.9	73.2	144.9	841.1
Dryland dairy	21.5	91.5	75.0	21.5	166.5	12.6	27.1	209.8
Blue gums (immature)	19.0	43.8	75.0	19.0	118.8	39.7	75.4	471.4
Irrigated beef	31.0	108.4	75.0	31.0	258.4	2.0	6.2	51.7
Irrigated dairy	76.5	454.5	150.0	76.5	604.5	14.6	111.7	882.6
Irrigated horticulture	1092.0	474.0	150.0	1092.0	624.0	0.4	39.3	22.5
Seasonal horticulture	0	84.0	0	0.0	84.0	0.6	0.0	5.1
Native vegetation	0.5	0.0	21.3	0.5	21.3	462.3	20.8	984.7

Source Catchments is a node-linked system where subcatchments can be based on stream topography and landforms calculated from a Digital Elevation Model that can be linked through nodes that represent river and stream reaches and confluences that terminate at a catchment outlet. The subcatchments are divided into Functional Units (FUs) grouped according to a common hydrologic response or behaviour based on combinations of landuse/cover (forest, crop, urban), management, landscape (flat, hill-lope, ridge) and/or hazard. Thus particular processes operate in an FU, commonly runoff generation, contaminant generation and filtering, which are not necessarily the same as landuse. However different landuses may have the same hydrologic response, and similar land uses may have a different hydrologic response. This allows calculations based on specific processes in each subcatchment of flows and loads to a specific node, providing a position in the catchment network where water management (e.g. extraction or demands) can be implemented. Links of water between nodes act as stores; routes where water and its constituents are processed allow for interaction with flood plains that are regarded as filters.

In the case of the Scott, land use for the model was divided into three hydrological categories (irrigated, cleared and vegetated land), and 14 landuse categories for nutrient generation (Hall 2011). The model was calibrated using flow from the gauging stations and nutrient concentrations at seven water sampling locations (Table 2.3).

Monitoring indicated that 72 GL of water flows from the Scott catchment each year. For the years 2000–2009, 11.2 tonnes phosphorus and 78.1 tonnes nitrogen left the catchment each year. Most of the nutrients were sourced from middle Scott, Four Acres and Dennis subcatchments with negligible loads from Molloy Island.

Loads from the main catchment outlet were slightly was less than the sum of subcatchment due to in-stream assimilation associated with flow in the highly vegetated reaches. Average loads were presented as there were large variations in annual loads, which are dependent variability in annual rainfall due to quantity, timing and intensity of rainfall in any year.

Phosphorus was exported primarily from the Four Acres and middle Scott subcatchments, primarily from areas used for dryland beef and horticulture, with smaller but significant quantities delivered from Dennis, Governor Broome, upper Scott, lower Scott areas. Negligible amounts were contributed from Molloy Island primarily because of the small size and relatively small septic tank contributions (Map 2.11).

Nitrogen was derived principally from middle Scott, Dennis and Four Acres, although the other subcatchments also delivered significant quantities. As for phosphorus, nitrogen exports from Molloy Island were very low.

The model was used to relate the output loads to particular sources, across the whole catchment and from individual subcatchments. This approach allowed the investigation of the specific activities as nutrient sources. Dryland beef and mixed grazing (30%) and irrigated dairy (33%) followed by immature blue gums (17%) accounted for the highest loads of phosphorus (Map 2.12). As dryland beef and irrigated dairies probably require similar inputs of phosphorus fertilisers but dryland beef occupied five times the area, these results suggest that irrigated dairies are probably applying more phosphorus than is required.

The major contributors of nitrogen were dryland beef, irrigated dairy, dryland dairy, immature blue gums and native vegetation.

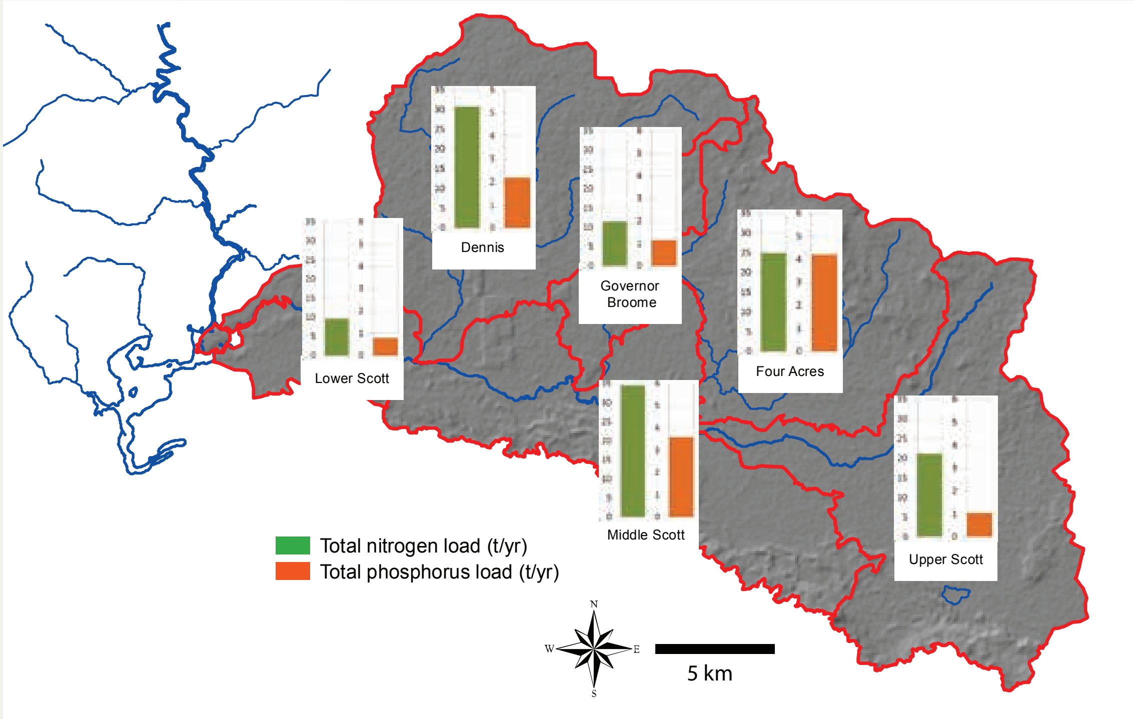
Using the model to address options for management practices

Based on the information about the predominantly agricultural sources of nutrients accounting for the high loads, a number of scenarios for adopting best management practices (BMPs) were examined. Four options for the Scott were:

- **Fertiliser management** through soil and plant testing to determine nutrient and the pH required, the optimal timing and spreading schedules, and budgets.
- **Effluent management** through containment and storage of effluent in lined settlement ponds for application to pasture as above — all dairies upgraded.
- **Riparian management** through riparian revegetation, rehabilitation, stream fencing, stock and vehicle crossings and off-stream watering for stock. This was limited to high order streams to minimise disturbance to agricultural land.
- **Soil amendments** included the application of phosphorus-fixing materials to sandy soils to reduce leaching and improve retention of phosphorus.

Table 2.3 Average annual flows, nutrient loads and load per cleared area, and median winter concentrations for the period 2000–2009 (Table 7.1 Hall 2011). Locations shown in Maps 2.10–2.12.

Summary	Lower Scot	Middle Scott	Upper Scott	Dennis	Governor Broome	Four Acres	Molloy Island	Total	Outlet
Flow (GL/yr)	5.2	15.4	16.5	16.0	5.2	13.3	0.2	71.7	71.7
Average annual load (2000-2009)									
Phosphorus load (t/yr)	0.78	3.61	1.05	2.17	1.17	4.22	0.01	13.01	11.21
Nitrogen load (t/yr)	9.6	34.5	21.3	30.8	11.6	24.9	0.1	132.9	78.1
Median winter concentration (2000-2009)									
TP concentration (mg/L)	0.14	0.22	0.06	0.13	0.22	0.3	0.06	-	0.15
TN concentration (mg/L)	1.81	2.11	1.23	1.80	2.19	1.74	0.51	-	1.00
Export Load per cleared area									
Nitrogen Load (kg/ha)	0.42	0.74	0.27	0.43	0.44	0.96	0.16	-	0.49
Phosphorus Load (kg/ha)	5.2	7.0	5.5	6.1	4.3	5.7	1.2	-	3.4



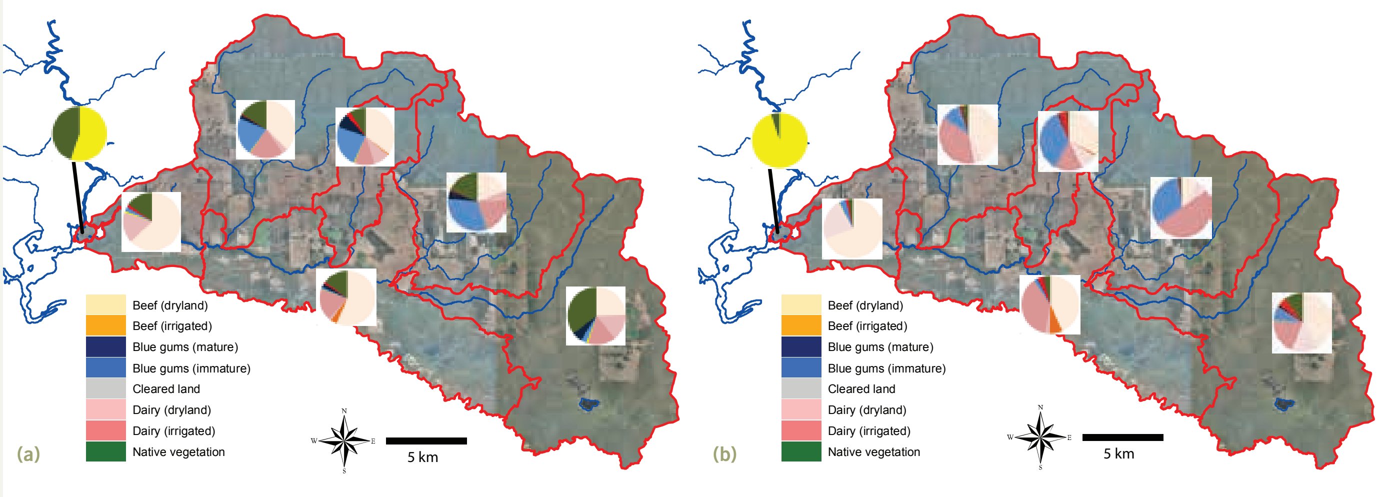
Map 2.11 Contributions to the total nutrient loads in the seven reporting subcatchments within the Scott River catchment.
Figure 7.5 from Hall (2011), courtesy DoW.

These options were incorporated modelling scenarios for best management practices in combinations of: fertiliser management; fertiliser and effluent management; fertiliser, effluent and riparian management; and fertiliser, effluent riparian and soil amendments.

The most effective management option to reduce nutrients was found to be management of the cattle enterprises. These showed the highest predicted reductions in phosphorus in response to improved fertiliser management practices (93%) and were also the best investment in terms of costs (fertiliser testing and technical advice) and benefits (reduced fertiliser costs). Similar management strategies in horticulture and blue gum plantations would account for almost all or the required phosphorus reductions.

Livestock effluent management was predicted to reduce phosphorus exports by 0.11 tonnes per year. The quantity of effluent although relatively small was of high concentration and a decrease likely to benefit the high-order waterways on the plain. Better management would also reduce associated coliform bacteria and other faecal contaminants that are a threat to environmental and human health. In the past, the relatively large initial capital costs and requirement for ongoing management were a barrier. However costs are now lower and requirements are linked to higher standards in dairy hygiene.

Riparian vegetation in the highly productive areas of the Scott catchment has largely been removed, although significant areas



Map 2.12 **(a)** Nitrogen and **(b)** phosphorus sources in subcatchments within the Scott River and Molloy Island to left with yellow indicating residential. The proposed new dairy in the lower Scott catchment may change the landuse from predominantly dryland grazing to irrigated dairy.
Figure 7.7 and 7.8 from Hall (2011), courtesy DoW.

remain in the lower catchment (Table 2.4 and Map 2.13). Generally, vegetation is most effective in reducing particulate phosphorus by trapping sediment in vegetation, however in the Scott River most of the phosphorus is soluble. Modelling predicted that restoring riparian vegetation in existing gaps very close to the main channel would only marginally reduce nutrients at a relatively high cost. However, other associated benefits include increased wildlife habitat and ecological corridors, biodiversity, and bank stabilisation, all of which can improve waterway health and enhance water quality. These added benefits highlight a potential shortcoming in analysing management options on a cost/benefit analysis only. It is also important to examine the costs of not implementing some riparian restoration.

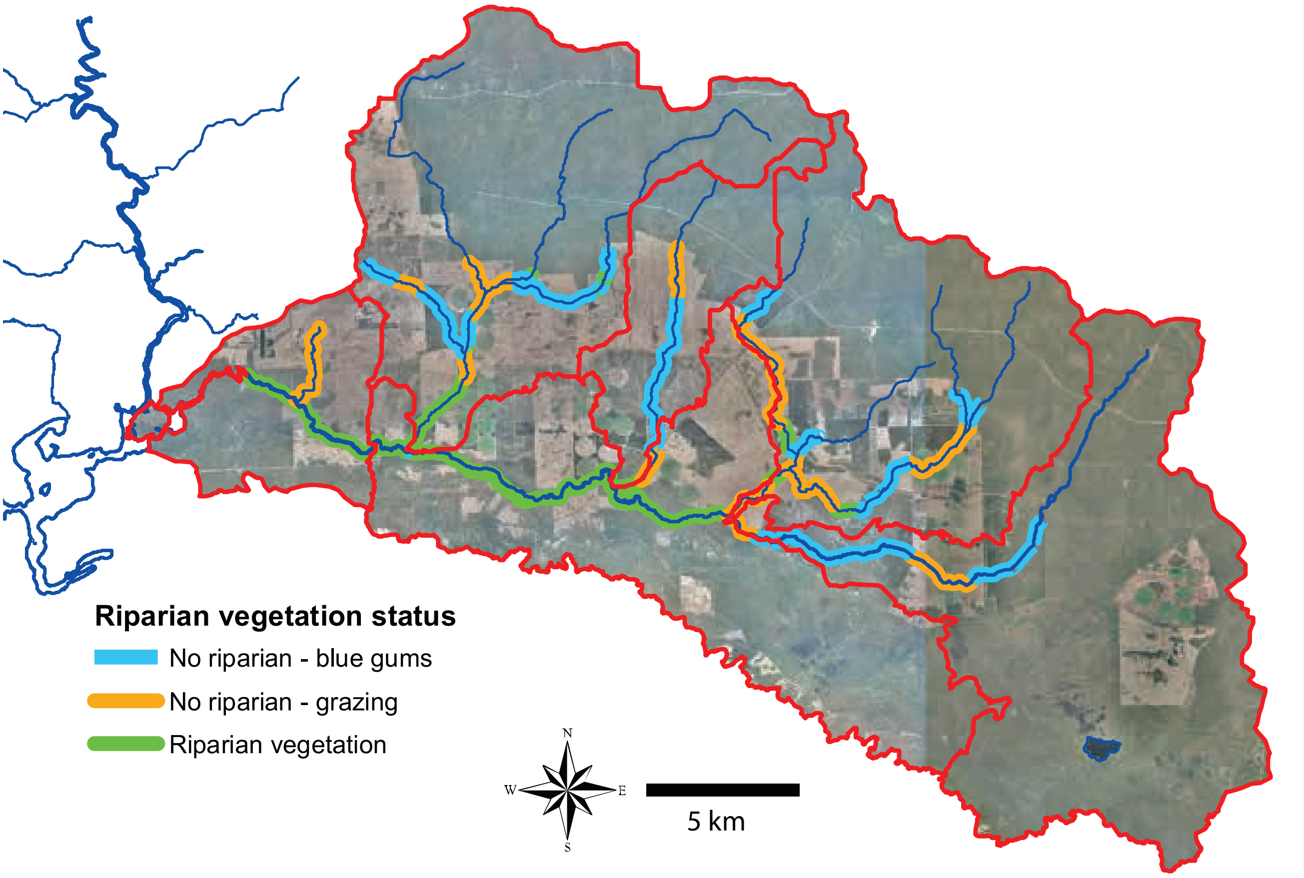
Table 2.4 Length of riparian vegetation and unvegetated streams. Unvegetated areas within grazed paddocks and within blue gum plantations, and unvegetated. Adapted from Table 8.1 Hall 2011.

Subcatchment	Riparian length (km)	Unvegetated length — grazing (km)	Unvegetated length —blue gums (km)
Lower Scott	10.3	3.6	0.0
Middle Scott	20.7	1.7	0.0
Upper Scott	14.4	4.0	10.4
Dennis	22.5	6.3	11.6
Governor Broome	8.1	2.0	6.1
Four Acres	27.6	15.6	8.7
TOTAL	103.6	33.3	36.8

Soil amendments to reduce nutrient loss have been successfully trialled in a number of situations. However, their suitability and viability in the Scott remain uncertain. The most cost effective product is Iluka's NUA (neutralised used acid), a co-product from the synthetic rutile process of heavy mineral processing. Other products have high transportation costs. However Iluka's NUA is not as yet available commercially, and paddock-scale implementation trials have not been undertaken. Currently cost/benefit analysis suggest that initially trials should be undertaken in blue gum plantations, and on a relatively small scale. Although the potential risks of NUA have been extensively quantified during field studies on turf farms, there is less information about exposure of livestock to soils treated with NUA (Hall, 2011).

Changing landuse in the Scott catchment

Landuse in the catchment in past decades has changed considerably in response to markets, and as the cost of resources such as water and fertiliser have risen. It is likely that catchment activities will continue to change. Currently the nutrients from irrigated dairies, which occupy only 2% of the catchment, are disproportionately high relative to much larger areas used for beef production.



Map 2.13 Riparian vegetation and unlined waterways, Scott River catchment. Figure 8.1 from Hall (2011), courtesy DoW.

A proposal for a new dairy in the lower Scott in an area previously used for dryland grazing is probably indicative of the direction of changes. The dairy would cover an area of 560 ha of which 292 ha would be irrigated. The effect of this development was predicted using the Source Catchments model, with assumptions that the rainfall runoff and nutrient export rates would be the same as those of irrigated dairies in the modelling described above. As the model indicated that the current dairies were probably over-fertilising, this would be likely to apply to the new dairy. However if the best practices for fertiliser applications were adopted at the outset, the increases in nutrient loads would not likely be too large (Table 2.5). Conservative estimates predicted nitrogen to increase by 2.5 tonnes/year (i.e. from 78.1 to 80.6 tonnes/year, an increase of 3.2%), with the concentration of effluent increasing from 1.00 mg/L to 1.04 mg/L, an increase of 3.9%. It was predicted that the phosphorus load would increase 0.47 tonnes each year from 11.21 to 11.68 tonnes/year, an increase of 4.1%, with the concentration increasing by 4.7%.

Table 2.5 Projected changes in nutrient load, concentration and flow as a result of a proposed new dairy development in the Lower Scott. Adapted from Table 8.5 Hall 2011.

Nutrient and flow status	Base case	Proposed dairy scenario	Increase (%)
Phosphorus load (t/yr)	11.21	11.68	4.1
TP concentration (mg/yr)	0.152	0.145	4.7
Nitrogen load (t/yr)	78.1	80.6	3.2
TN concentration (mg/yr)	1.00	1.04	3.9
Flow (GL/yr)	71.7	72.1	0.5

The model also predicted an increase in flow of 0.4 GL/year (0.5%), as water used for irrigation would maintain soil moisture year round. As a result rainfall would have an immediate effect on runoff rather than recharging soil moisture after a dry period.

2.8 Future influence of the Blackwood and Scott catchments

The *Hardy Inlet water quality improvement plan Stage one — the Scott catchment* (White 2012) summarises the Department of Water's recent research of factors affecting the Hardy Estuary's health, and details the long-term plans for protecting the system. The Scott model (from Hall 2011), *Scott River catchment hydrological and nutrient modelling*) was found to be a suitable basis on a catchment scale for estimating flow and nutrient export and for evaluating potential improvements if land use changed or management strategies were implemented. However, the models require further development where detailed cost and benefit analyses on the finer scale of farm or paddocks are undertaken. Similar analyses and modelling being conducted on the lower Blackwood and Augusta townsite will provide information for further management.

The most effective management changes in the Scott catchment would be modifications of fertiliser use in cattle production. Furthermore, research across the south west indicates that soils currently hold phosphorus stores in excess of requirements for maximum production. For dairy farmers in the Scott this amounts to five times the required phosphorus each year (White 2012). Reduced fertiliser applications could provide a benefit to the estuary downstream but also reduce immediate and future fertilisers costs.

Overall reductions in nutrients to meet the water quality objectives in the upper Hardy Estuary near the Scott River Molloy Island junction equate to 28% reduction of the current phosphorus load and maintenance of the current nitrogen load (Table 2.6).

The Scott therefore adds to the story of other waterways in south western Australia with the recurring theme of needing to reduce phosphorus. Results of the modelling support calls for no longer delaying implementation of the FAP by the Joint Government Fertiliser Industry Partners. These include testing to determine the soil stores, the type of nutrients required and the application of material to increase retention of applied nutrients. As yet trials for reducing fertiliser loss from soils have not been conducted on a suitable scale and may not be as effective as reducing the initial applications.

Table 2.6 Current and target nutrient loads from the Scott catchment entering the Hardy Inlet. Adapted from Table 4.2 White 2012.

Nutrient	Winter median concentration (mg/L)		Average annual load (t/yr)	
	Current status	Target	Current status	Target
Total phosphorus	0.15	0.10.	11.2	8.1
Total nitrogen	1.0	1.0	78.1	78.1

Riparian management was predicted to have smaller nutrient benefits at relatively high cost. However other benefits of riparian vegetation such as providing a habitat for wildlife, shade and stabilisation of banks, would suggest that maintenance and restoration should not be considered in terms of nutrient reduction alone.

Clearly the large reductions in water flow experienced over recent decades are not related to changes in rainfall, which has remained quite consistent in the Scott catchment in comparison to the Blackwood. The interaction between aquifer draw down and groundwater and river flows remains debatable. Similarly the negative effects of declining flows on the river ecology have not been studied. The now widely identified problems of increasing acidity on the Scott Coastal Plain and potential issues for agricultural production and water quality pose other areas of concern.

Until recently the lack of data on nutrient reductions and the costs and benefits associated with different management practices have prevented accurate assessment of many management practices, which remains a priority. The impost of increasing land degradation in the face of projected changes in rainfall and competition for limited resources may lead to requirements for greater interest in addressing downstream effects.

View to Colour Patch, lower inlet channel, April 2008. A. Brearley

Chapter 3

THE ESTUARY — PHYSICAL FACTORS

Chapter 3

The estuary — physical factors

3.1 Geomorphology of the Blackwood Estuary — Hardy Inlet

In their 1978 summary of the Blackwood Estuary, Hodgkin and his colleagues stated that: *Estuary is here defined as the tidal part of a river system; it is a region where freshwater and seawater mix, at some time of the year, and includes coastal lagoons which are continuous with it*. They noted that this was appropriate to the Blackwood and other estuaries of south-western Australia. And further, that the estuaries were on a coastal plain across which a tidal river winds to discharge into a basin or lagoon behind Pleistocene dunes that restrict the mouth. While the term 'inlet' is generally poorly defined, in the case of the Hardy some geomorphology and biotic components could be used to define specific areas (Figure 3.1 and 3.2). In the 1970s the system was divided into the following elements:

Inlet Channel: The narrow part of system connecting the mouth and basin, this being the area bordered by the Augusta townsite and residential area of East Augusta.

Basin: The lagoonal part of the estuary between Point Irwin and Island Point. In some technical reports it is termed the 'lagoon'. The shallow upper part of the basin is the river delta, referred to as the delta.

Tidal River: The estuary upstream of the basin and Island Point. The lower part of this is around Molloy Island, with extensive shallow margins and intertidal swamps characteristic of the basin, however the main river channel is over 100 m wide and 5–10 m deep. The river channel is of similar dimension between Molloy Island and Alexandra Bridge with small lateral lagoons and swamps where tributaries enter. Between Alexandra Bridge and Warner Glen Bridge it is narrower, but much of it is five metres deep. There are shallows and a rock bar about 42 km from the mouth, which obstructs river flow and appears to mark the upstream limit of marine water penetration but the river may be tidal to a ford at Carey's Flat (55 km). The banks are high and steep between both bridges and continue so to well below Alexandra Bridge.

The Scott River is also tidal for about eight kilometres where an ironstone bar limits the upstream movement of marine water.

Deadwater and Swan Lake: The Deadwater lies east of the estuary mouth, and opening to it by a narrow channel, inland of the Swan Lake. The Deadwater is, or was, a persistent river channel during 1930–1945. It is up to five metres deep but most of it is less than two metres and gets progressively shallower at the eastern end.

Molloy Island March 2012, at the junction of the Scott River (left) and the Blackwood River (foreground). Courtesy Brian Combley.

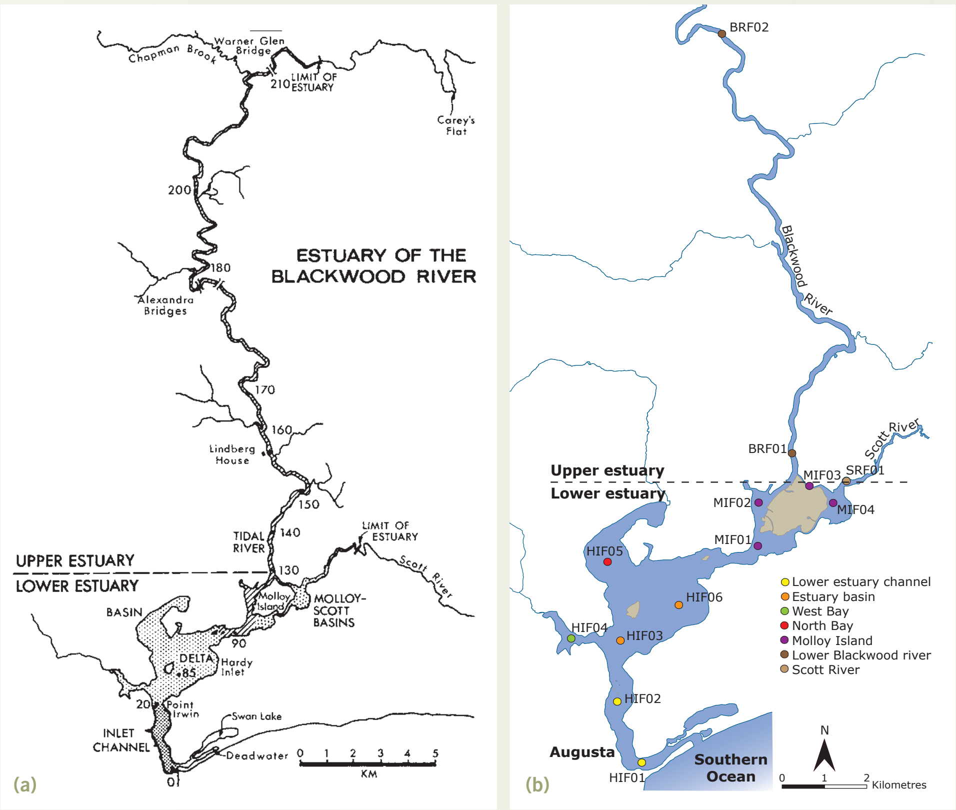


Figure 3.1 Hardy Inlet locations. **(a)** Terminology used in the 1970s study (Hodgkin 1978). **(b)** Locations of water quality monitoring 1999–2011. Courtesy V. Forbes DoW 2012.

Swan Lake is connected to the Deadwater by a channel winding through the dunes. Until the 1920s, it was a shallow, seasonal, freshwater area. Disruption of the dune system allowed the seawater to enter. In the 1970s the lake, about one metre in depth, was a productive aquatic plant habitat.

The length of the Deadwater has decreased since the 1980s due to the development of the sand bar and dunes from Dukes Head and the gradual eastwards deflection of the inlet channel.

Terminology used in reports vary between studies and include a number of subdivisions of the Basin into Delta, Basin, Molloy and Bays based on slightly different water flow, sediment regimes and algal communities. Other researchers investigating water quality, nutrients and algal blooms have considered the system as two zones: the saline zone and the mixed zone. However the use of the upper estuary and the lower estuary as defined by Hodgkin (Figure 3.1) is generally useful.

Infra red image 1974 showing topography, vegetation and sand banks of the Hardy Inlet. EP Hodgkin Collection.

Eastern mouth of the Hardy Inlet, August 2010. Courtesy V. Forbes DoW.

3.2 Holocene sedimentation — estuary development

The 1974–1975 sedimentation study examined the role of environmental processes in the deposition and construction of the marginal platforms and the river delta, and how these might be affected by mining activities. When considering sedimentation in an estuarine environment, Hodgkin thought it essential to keep in mind the great changes in sea level during the Pleistocene glaciation. Although there have been fluctuations of up to three metres over the last 5000 years, changes prior to this were much greater. About 15,000 years ago, the sea rose from a glacial low of 100 metres below the present level. At this time the coast at Augusta would have been much further south, beyond the islands, with the present estuary a valley with a river running through it and entering the sea possibly in the vicinity of the Leeuwin Canyon. (For a discussion and map of the Leeuwin Canyon see *SWANLAND* p11, Map 1.6). The estuary as we know it evolved, after this stage in the post-glacial Holocene period, as the sea rose and flooded the older basin. Sediments would have first accumulated in the old river channel, to some extent the deeper parts of the present estuary. However the 1974 drilling program did not reach the bottom of this unit, and the location of the old river channel was not identified. At this time the basin would have been much larger, with a volume estimated of 22,000,000 m^3 compared to the 1,000,000 m^3 of the present basin. It would have covered parts of the Scott Coastal Plain.

The lower estuary lies to the west of the Dunsborough Fault, which runs through the main basin. In the west, the Precambrian granitic rocks of the Leeuwin-Naturaliste Ridge rise steeply, outcropping at Lion Island and on the eastern bank at Point Irwin. While much of the east bank is sandy and low-lying, limestone about two metres high outcrops along the southern section. The flat-bedded, coarse-grained Tamala limestone contains marine fossils deposited about 120,000 years ago when the estuary was flooded during the Pleistocene. Some of the molluscs and coral are warm water species that no longer live in the area. One section of the Augusta Shell Beds about three metres above low water is listed as a Geoheritage site (Number 77, Geological Survey of Western Australia) (GSWA) based on fossils held in the Western Australian Museum and documented by G W Kendrick and reported by Carter 1987. It is also listed in the Australian Heritage Database #18280. The area lies within Shire Recreation Reserve #25211 (see photograph Chapter 2, Page 8).

Investigations in 1974 included a Hydrographic Survey by the Harbour and Rivers Branch of the Public Works Department and the production of two charts, from the mouth to Warner Glen Bridge (1: 5000 scale, PWD, WA 48913) and lower estuary 1:15,000 (PWD, WA 46913). The Geology Department of UWA collected cores at 67 locations within the estuary and others on the eastern bank (Sas 1974, Hodgkin 1978).

The cores revealed that the sediments we see today were deposited during the last 5000–7000 years over a basement of sandy **Pleistocene** soil (Figure 3.2). In the west, this is orange sediment and white ‘china clay’ or kaolin derived from weathering of the granitic rocks. In the east, the coarser sand was probably reworked from the dunes.

Although the mantle of younger material varies greatly in thickness, representing different times and conditions, several phases are evident. At depth, the **Basal Sheet** (about 0.2–0.8 m thick) consists of resorted older material together with remnants of terrestrial plants and estuarine animals. The **Oyster Unit**, which is about two metres thick, is predominantly 4000 year old fossil bivalve shells, including the mud oyster *Ostrea angasi* which lives today in Oyster Harbour, together with thick black mud and burrowing worms. This unit probably represents an early stage of estuary development when seawater entered more freely. The Oyster Unit is overlain near the bar by the **Inlet-bar Unit** of beach sands mixed with material from the older dunes, shelly material and sponge spicules of marine origin. Upstream it is overlain by the black organic mud and fine quartz sand of the **Basin Unit** together with plant debris and faecal pellets, shells and worm tubes. The fossils indicated that while some of the species still lived in the system, others no longer present were characteristic of a more marine period. The upstream section of the Basin Unit is overlain by the **Delta Unit** formed of layers of medium to coarse river sand, mud and plant debris indicative of varying river flow and wave disturbance during the estuary’s development.

Hodgkin and colleagues (Sas 1974) considered that the differences in the sediment reflected a large variation in the annual volume of river discharge, but also noted that the form and dimensions of the

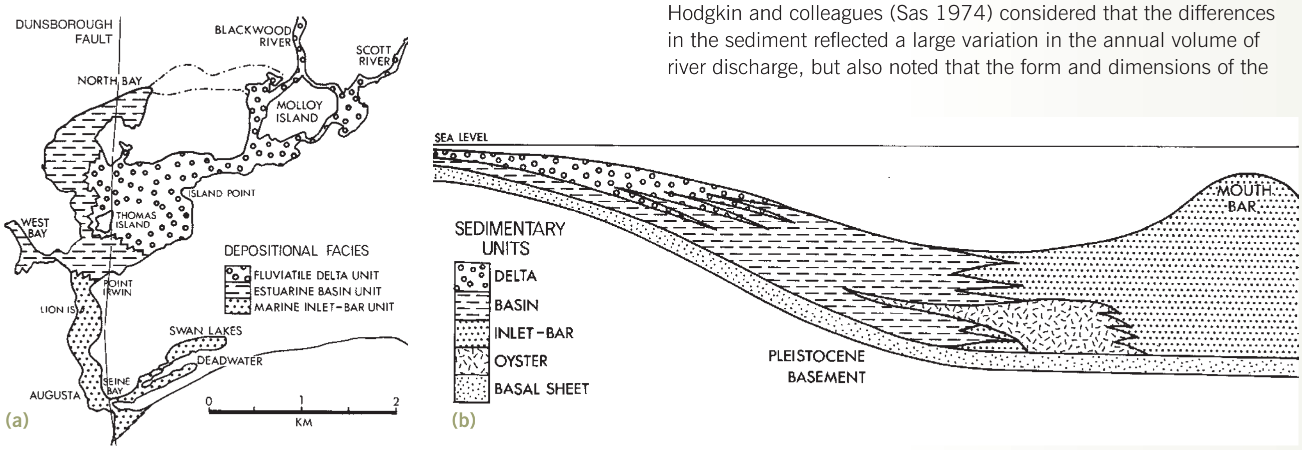
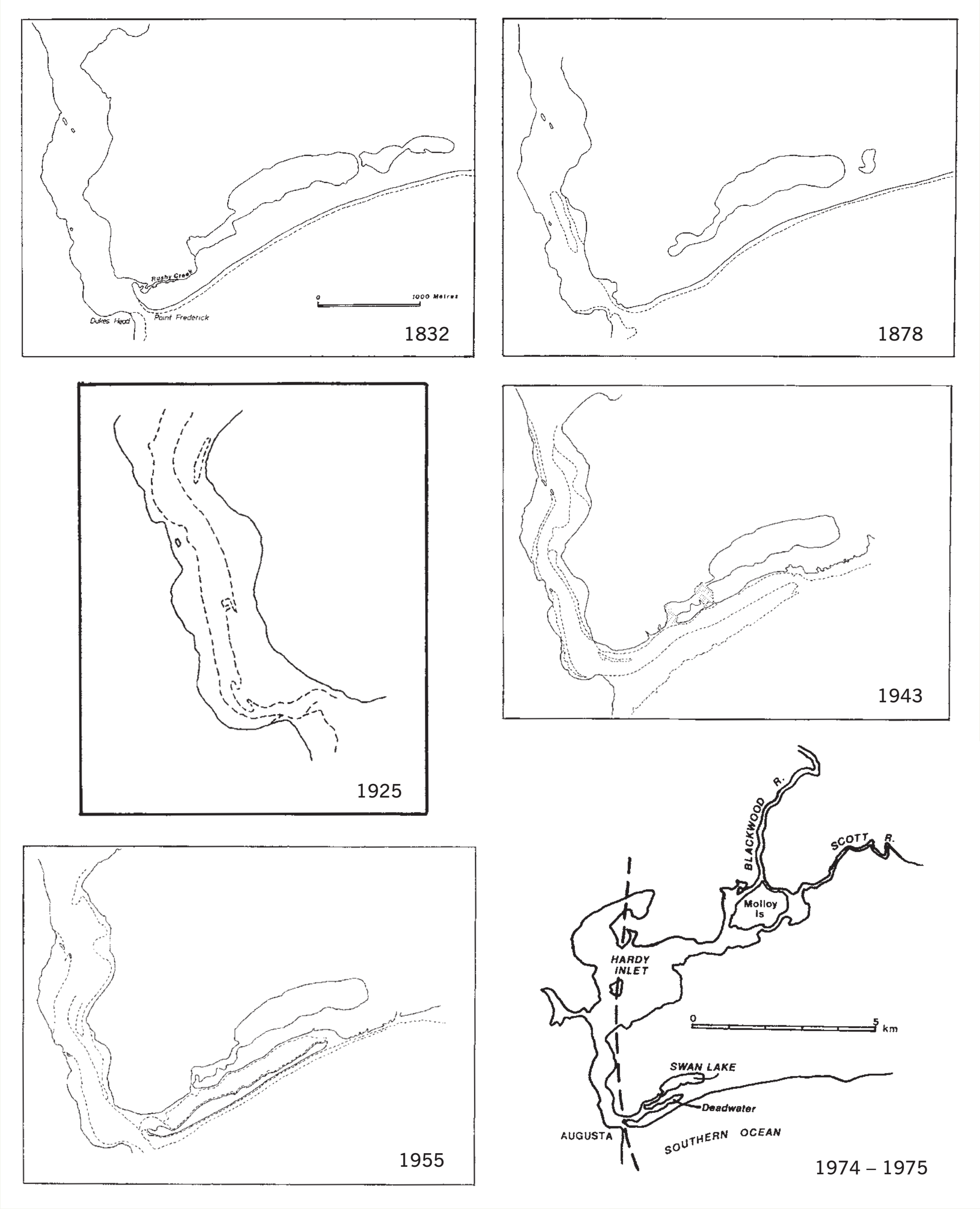


Figure 3.2 Sediments of the Blackwood River estuary **(a)** surface sediment **(b)** idealised stratigraphic section. Sediments grain size was examined to determine the probable behaviour of sediments if resuspended by dredging or other processes (Sas 1974). The Pleistocene unit contained poorly sorted material. The Delta unit predominantly contained sand-size material brought during high river flow, but with 25% silt-clay fraction. Basin unit was largely of organic material deposited under low flow conditions with 80% silt-clay fractions. Inlet Bar, the best sorted unit with medium to fine sand but 13% silt-clay fraction. It was noted however that fine particles are bound by electrostatic forces and that biota also bind sediment. As a result sediments are more resistant to shear forces from river flow than indicated solely by grain size. Adapted from Hodgkin, 1978. See also *SWANLAND* Brearley 2005.

lower estuary, as indicated by the drilling program, had not changed markedly in the last 6000 years. Except for a few restricted localities, there was little evidence of more extensive erosion of the banks or much prograding by the swamps. Regarding the depositional changes this was of ‘*infilling of the Pleistocene Basin with the deposition of more than 8 m of sediment, and a massive accumulation of marine sand to infill the inlet, and form the bar leaving a central flood channel and marginal platforms.*

‘*The Holocene sedimentary processes continue at the present day. The estuarine mud continues to accumulate where it is relatively undisturbed in the deeper sections of the basin and delta sand continues to prograde over it. There is no evidence of the net rate of deposition at the present time; it can be quite rapid locally and the northern channel has silted up and become almost impassable this century.*

‘*The most striking change which has taken place since 1830 has been the formation of the Deadwater and the consequent incorporation of this and Swan Lake in the estuarine system (Hodgkin, 1976). The event and the observed movements of banks inside and outside the mouth, underline the great mobility of sands of the Inlet-bar unit here. On the other hand, the record also serves to emphasise the dynamic stability of sedimentary processes within the inlet. This leaves it an open question as to whether there is continued accretion to the Inlet-bar unit or whether this is now in equilibrium with the constructive forces of tidal transport and the destructive effects of the very varying winter flood discharge and storm waves.*’ (Map 3.1).



Map 3.1 Configurations of the mouth of the Hardy Inlet, adapted from illustrations published by E.P. Hodgkin in the 1976 J. Roy. Soc. W.A. 59: 39–45. Map dated 1832 Hillman, Turner and Edwards; 1878 Admiralty Chart; 1925 Hydrographic Survey (PWD 23962) Rushy Creek flow from Swan Lake to the main inlet channel.; tracing of air photo 1943 with stippled areas indicating bare sand thought to be the result of attempts to block the creek. Broken line indicates the line of the Dunsborough Fault. Small dashed lines on all maps indicate sandbars.

Adapted from Hodgkin 1976.

3.3 Development of the bar 1976–2010

The entrance of any estuary into the ocean is always fascinating. The continual movements of water into and out of the system, and of sand accumulation and erosion, affect many aspects of an estuary. The Hardy Inlet is no exception and the sea bar changes are particularly well documented.

Development of the Deadwater and movement of the bar was noted by Hodgkin as the most striking change in the system since the 1830s. It was a subject of great interest, prompting a publication (Hodgkin 1976) documenting changes at the mouth of the Hardy as recorded in paintings, hydrographic charts and photographs. This illustrated Hodgkin's continuing interest in bar development in other estuaries and the evolution of estuaries over time (Hodgkin and Hesp 1998). Such changes along the coast are much debated as the shallowing or closing of estuarine bars affects the flow of water into and out of a system, influences flooding, salinity, accumulation of nutrients, and access for boating and for marine life, particularly fish. Hodgkin noted that although the sand barrier in the Hardy never closed completely and the tidal channel was quite deep, sand obviously accumulated offshore outside the channel, where waves indicated that the sea bar was less than two metres deep in summer, or as noted on the Admiralty Chart of 1878 at a depth of one fathom (Map 3.1).

The 1943 channel (Map 3.1), occupied by a coastal lagoon called the Deadwater, connected to the river mouth by a deep channel through a broad shallow bar of mobile sand at its western end. The eastern end had silted up but did not appear to be vegetated. Hodgkin's summary of the aerial images from May and December 1955 suggested that the position of the mouth, and form and dimensions of Dukes Head and Point Frederick, were essentially the same as shown in the 1832 map.

Twenty years later, in 1975, the only significant differences were the development of the fore dune and establishment of vegetation along the entire bar. The more recent, circa mid 1980s, formation of the bar from Dukes Head and diversion of flow through the Deadwater reinstated conditions similar to 1945 (Figure 3.3a and b), before the bar was breached during floods in 1946. This leads to questions of what initiated the large changes.

Movements of sediment along a coast depend on the availability of sand, and direction, strength and persistence of waves that bring sediment onshore, across-shore and along-shore. In the case of an estuary, there are also the competing processes of out-flowing water and the variation of flow throughout a year and from year to year. Flow redistributes sand stored in the sand banks and along the channels, and modifies flow direction within the estuary. A consultant engaged by the Blackwood Basin Group and the South West Development Commission (Masters 2008), suggested that a change of flow direction resulted in erosion of the eastern bank and Point Frederick, and favoured development of a spit from Dukes Head. However, behind these ideas lies the question as to why the direction of flow within the estuary changed. Dredging through the natural delta channel in 1956, 1973, and 1998 (DAL 1997 and DoT records 1998) to provide deeper boating channels could be part of the answer. The deeper dredged channel probably increased flow on the eastern side and decreased flow through the more circuitous route along the north side of the delta past Point Pedder and along the western side of the inlet. The deeper channels could have modified the rate of flow and activated unstable areas in the downstream channel profile with subtle change in direction initiating erosion at the entrance.

At the entrance, with erosive forces initiated, eastward bar growth could be due to dune erosion, mobilisation of sand and transport from east to west. Decreased river flow no doubt caused a major change to flushing and maintenance of an open channel. However, the time a channel remains open depends largely on the persistence of swell conditions that activate the cross-shore movement of sand in summer,

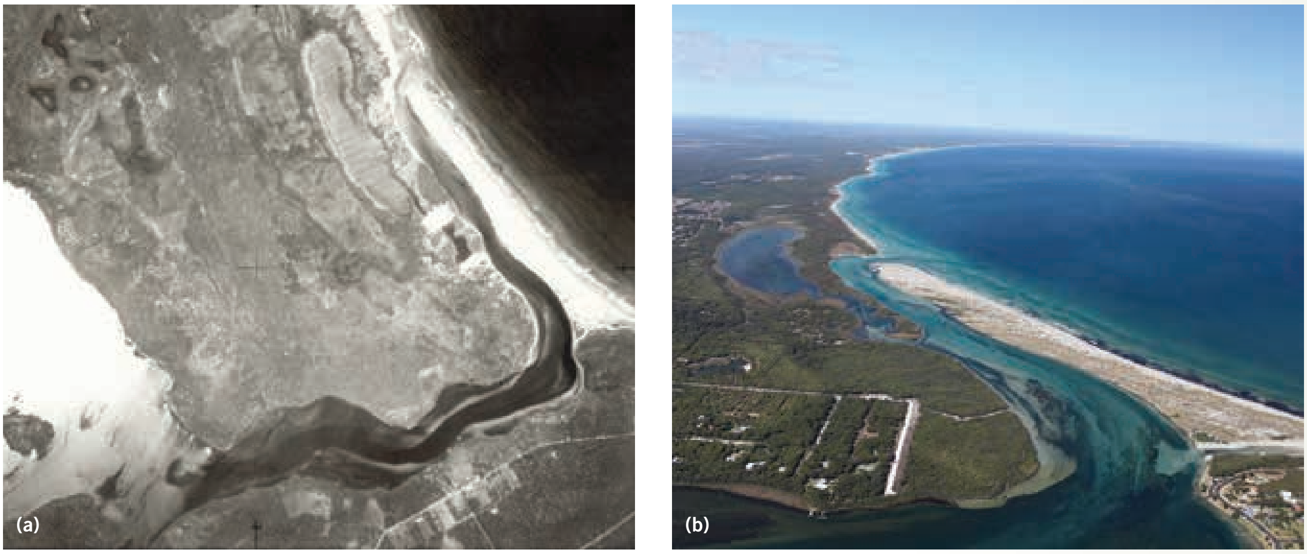


Figure 3.3 (a) Aerial Image of the Hardy Inlet entrance 1943. The passage through the bar is similar to that of the entrance in 2010. RAAF photograph #27738 Map 1136 Busselton-Karridale Run 2. After a channel on the western side of the bar was excavated in 1945 and floodwaters scoured a deep channel the position of remained in much the same location although is shallowed substantially and boat traffic to the ocean was at time difficult. By 1982 the entrance was moving eastwards as sand accumulated at Dukes Head and eroded from Point Frederick. **(b)** 2011 configuration of the inlet channel showing the similarity to 1943. Courtesy Brian Combley.

Figure 3.4 Entrance Channel. **(a)** View to estuary, October 2010 **(b)** View seawards to Flinders Bay, January 2012. Excavations commenced in August 2010 through the sand bar in the vicinity of the ocean opening, 1946 to circa 1982, cost $30,000. Excavations commenced on 13 August and concluded on 18 August, coinciding with maximum high tide. Sand that accumulated in the channel during floods tides was removed on two occasions but the channel gradually widened and became shallower at the seaward end. In the foreground is the outcrop of gneiss revealed as the flow moved sand along the channel. Details of excavations courtesy of the Augusta-Margaret River Council 2010 and 2012. A. Brearley.

as indicated by modelling of different flow scenarios and bar closure at Wilson Inlet (Ranasinghe and Pattiaratchi 1999). Conditions favouring development of a sand bar at Augusta are likely be similar to those that do so at Wilson Inlet, as both estuaries are located in large bay sheltered on the west by a headland and open to oceanic swells from the Southern Ocean. While the westerly shelter provided in Flinders Bay by the rocky coastline through to Cape Leeuwin may not appear to provide the same protection as Wilson Head, use of the bay as a winter timber port in the 1800s when Hamelin Bay on the west coast was not accessible attests to its effect on swell direction and strength (Map 2.1).

Low river flow, cross-shore movement of sand from Flinders Bay, the contribution of sand from shoals in the once shallow Deadwater and the primary dunes built since the 1980s no doubt all contribute to the dynamic movement of the bar. Although comments have been made about loss of the Deadwater environment, many of the attributes of the area — shallow, sheltered water with a rich growth of *Ruppia* — have not been 'lost' but relocated to the foreshore area of Seine Bay. The other aspects of a more eastern ocean opening are also debated and so far open to conjecture (i.e. the effect of flushing, flooding and inconvenience for boating). Memories of the 1945 flood, concerns that flood waters could bank up behind the sand bar and inundate low areas around the estuary provided the impetus to open the bar on the western side.

A new channel through the dunes was constructed in August 2010 in the area of the 1970s opening (Shire of Augusta-Margaret River 2010). When the bar was breached, outflow widened the channel and some estuarine water flowed out. However the incoming tide transported sand into the channel, infilling the ocean end. Excavation of the sand was attempted on two occasions and although the outflow cleared the channel sand, the sand accumulated again with the incoming tide. As a result the channel became wider and deeper at the river end and wider and shallower at the sea. In mid October 2010 only shallow water covered the inlet side of the channel. The channel became rapidly shallower to seaward until there was no exchange between the inlet and ocean. Tidal flows through the still-open eastern entrance were strong. Erosion of the channel banks and dunes bordering Swan Lakes and redeposition of sands along the bar and in shoals off shore were clearly evident (Figure 3.4 Brearley unpublished observations). In August 2011, heavy rain in the catchment increased flow. This coincided with a period of higher high tides and lower low tides, and further excavations removed the sand and reinitiatied flow. The bar was also opened in August 2013.

The reconfigured western channel, while non-functional in late 2011 in terms of water exchange, lies in wait for a hoped-for strong river flow that could push the newly accumulated sand seaward. When, and if, this happens is of course difficult to predict. The eastern channel behind the now consolidated dunes may continue to provide an 'easy' pathway through to the ocean. A successful western opening could lessen the distance of water passage and may provide a better, although shallow, boating channel, and reduce the effects of flood waters, but its effectiveness as a 'cure' for the other major issues of water quality remains to be seen. The low-lying areas most likely to be affected by floods could equally be inundated when sea level is high. To date in the Hardy, there have been no scientific studies on the mechanisms of sand movement, the development of the bar or the likelihood of floods.

3.4 Recent sediment deposition following development of agriculture

Estuaries are depositional environments where sediments and nutrients derived from the catchment continually accumulate. This provides a record of changes in water flows and activities in the catchment. Investigation of sedimentation in the Hardy Estuary in response to clearing and erosion since European settlement was secondary, although complementary, to the primary focus of the Geoscience 2007–2008 studies: assessment of nutrients in the sediment, movement of nutrients into the water column, and potential for aquatic plant growth (see Section 3.6). The studies complemented research programs in other south-western Australian estuaries and provided an opportunity for assessing differences and similarities of sedimentation and nutrient cycling processes operating in different systems.

Two cores, 70–80 cm in length, were collected from the channel downstream from Molloy Island in the area described by Hodgkin as the Fluviatile Delta Unit (Figure 3.1) to determine the sediment ages at different depths and sedimentation rates in response to environmental changes. One core (HD 34A) was cut into two centimetre units for examination of sediment grain size and composition (bulk density) and pollen analysis (Figure 3.3a). The other core (HD34B) was frozen for chemical analysis and dating using the decay rates of natural and artificial radionuclides (Lead as $^{210}Pb_{excess}$ and caesium ^{137}Cs) for recent sediments and Optically Stimulated Luminescence of quartz grains for older sediments at the bottom of the core.

Both cores showed distinct changes in sediment characteristic at depths of 26 cm (core A) and 42 cm (core B). In core A, (Fig 3.5a) the sharp change in sediment characteristics (bulk density) between 26 and 22 cm indicates a difference in grain size from muddy to coarser sandy sediments, with a gradual decline in size towards the surface. The number of fossil pollen and spores also declined at this depth and remained low to the surface. Pollen, predominantly *Pinus* and exotics including dandelions (Asteraceae), at the surface to a depth of 13 cm, were thought to represent the present period to 1920. Pollen attributed to the seagrass *Ruppia* was present throughout the core but increasingly abundant in the top nine centimetres. Pollen from *Melaleuca* (paperbarks) and *Casuarina* typical of the inlet area were also present.

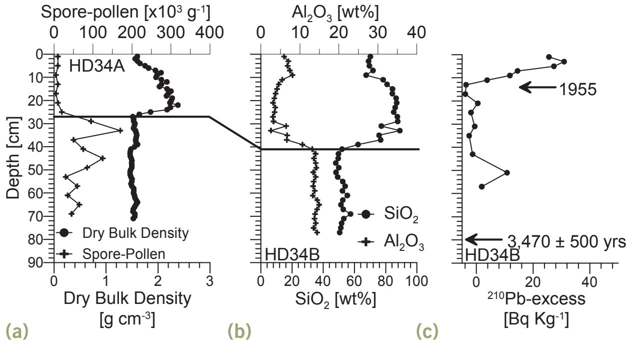


Figure 3.5 (a) Dry bulk density and total number of spores and pollen, **(b)** Chemical composition: Aluminium Al_2O_3 and Silica SiO_2 **(c)** Lead ^{210}Pb. The deepest section core dated using Optically Stimulated Luminescence (green laser) OSL as 3,470 ± 500 years. Haese *et al*. 2010c. Courtesy DoW.

Deployment of a benthic chamber for investigating nutrient fluxes 2008. See also Figure 3.7. Courtesy Geoscience Australia and DoW.

The sharp change to coarse material and slight return to finer material probably results from sub-soil erosion at the time of land clearing, and the gradual revegetation with exotic species *Pinus*, Asteraceae and *Casuarina*. The lower pollen content in the upper part could indicate less production of pollen and spores since clearing.

The increase of *Ruppia* indicated by more abundant pollen in the top nine centimetres was considered a response to rapid infilling and increase in the area of shallow water suitable for seagrass. In addition, the more recent decrease in sedimentation and water clarity after World War II provided better conditions for growth. The now prolific growth of *Ruppia* is also indicative of the high nutrients in the system as it is in other estuaries such as Wilson Inlet and the Peel-Harvey.

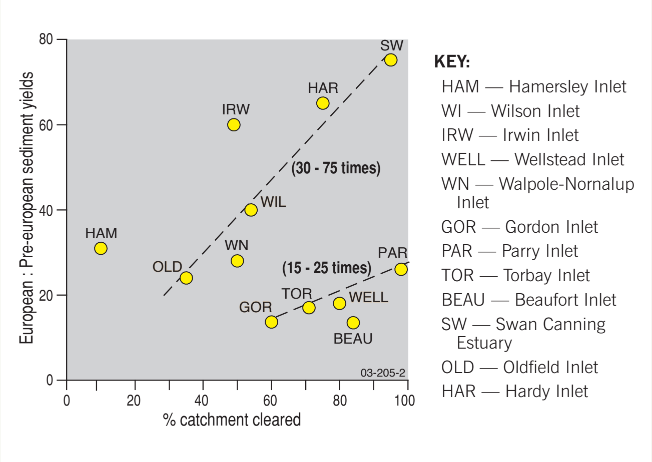
In the second core HD 34B (Figure 3.5b), the chemical composition also changed with depth, from aluminium-dominated in the deeper section to silica-dominated between 42 and 32 cm. The aluminium-rich section typified clay minerals and fine sediments, and the silica-dominated sediment coarse-grained minerals such as quartz and feldspars.

The dating analysis of the different sediments using lead $^{210}Pb_{excess}$ indicated the top six centimetres of sediment was very consistent and indicative of mixing (bioturbation) by burrowing animals. The low concentrations of lead $^{210}Pb_{excess}$ (Figure 3.3c) and caesium ^{137}Cs (not included in the graph) in the surface sediments were attributed to low volumes of topsoil in the estuary. However between six centimetres and 12 cm, the $^{210}Pb_{excess}$ and ^{137}Cs decreased linearly. As ^{137}Cs was introduced to the global environment through nuclear bomb tests in the early 1950s, the sediments at 12 cm were presumably deposited at about 1955. Calculations using the sediment interval 6–12 cm and the known half life of $^{210}Pb_{excess}$ of 22.3 years, indicate a sedimentation rate of 0.11 cm y^{-1} since 1955.

Similarly the assumption that the sediment change in core 34B at 42 cm (and core 34A at 22 cm) represents the initiation of clearing in 1880, and the sediment at 12 cm was deposited in 1955, 75 years later, implies a deposition rate of 0.4 cm y^{-1} for this earlier period. Coupled with the age at the bottom of the core of 4370±500 years and the age of the change at 42 cm of 128 years, the average sedimentation rate for the period preceding European clearing would be 0.01±0.02 cm y^{-1}. Thus there has been a ten-fold increase in sedimentation since pre-European time from 0.01 to 0.11 cm y^{-1}, with erosion and sediment deposition particularly high during the initial phase of clearing (0.4 cm y^{-1}). These sedimentation rates are very similar to those indicated by cores at Stokes Inlet (Murray *et al*. 2008 (Figure 3.6) (Haese *et al*. 2010). The sediment yield of 97.6 kT y^{-1}, with a European:pre-European sediment yield ratio of 65, is only exceeded in the South West by the Swan-Canning (165.4 kT y^{-1} and a ratio of 75), which has a much higher catchment area (Radke *et al*. 2004).

The consistency of ^{210}Pbexcess throughout the upper section of the core indicates that, unlike cores from Stokes Inlet which had a distinct change indicative of a flood event, sedimentation in the Hardy is more likely to be a continuous rather than a single pulse event. Based on the historic records of agricultural development, it is likely that these changes can be related to initial land clearing.

Since European settlement, sediment in these estuaries (Figure 3.6) has increased 15–70 times, at a rate of 0.1 to 7.8 kg m^{-2} y^{-1}. The Oldfield and the Hardy have the highest amounts of carbon and nitrogen, which could affect estuary health. There is a clear relationship between the weathering and sediment loads. The rising curve probably relates to soil erosion, and the decline to bedrock erosion with movement of more primary minerals and less clay. Water quality, as concentrations of TN and TP tend to be double guidelines when sediment loads are 2-4 kg m^{-2} y^{-1}, and weathering is higher than 67. Where sediment loads are high, chlorophyll a concentrations are also high and algal blooms more common. The Oldfield and the Hardy have good quality water based on nutrients and chlorophyll a, but poor sediment quality based on the (Total organic carbon:Total sulfide) TOC:TS ratios.



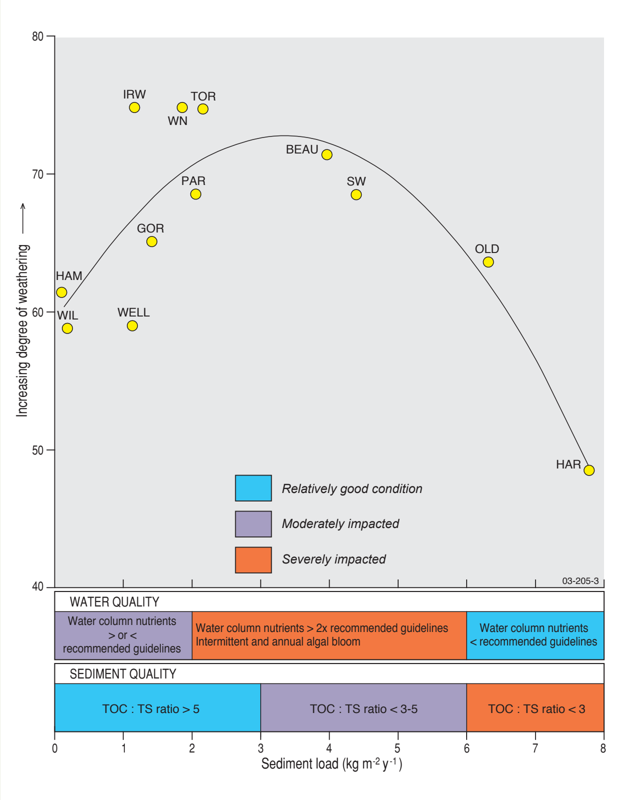


Figure 3.6 Relationship between catchment clearing and sediment yields in 12 south-western Australian estuaries (Radke LC 2003 *Land Clearing swells sediment loads in WA estuaries* in AUSGEO News Geoscience Australia 72: 18–19). The low ratio TOC:TS indicates increasing sulfidation probably due to enhanced burial of reactive organic matter and reduced contact with oxygen. Therefore organic matter can accumulate in the sediment where it is more likely to be degraded by sulfate reduction, biogeochemical process that releases nitrogen and phosphorus in forms suitable for algal growth. Courtesy Geoscience Australia.

3.5 Sediments and nutrients

It is natural for sediments to accumulate in estuaries that are at the end of river system and at a low point in the landscape. However, it is not natural in the Hardy Inlet where the rate of sedimentation has increased ten-fold since the 1830s when activities in the catchment changed. Increased sedimentation is usually accompanied by an increase in organic matter and nutrients (Section 2.6 and 2.7) (Figure 3.5b) that are associated with fine sediments. Plant and animal growth also contribute organic matter to the sediment that increases the potential for decomposition and the release of nutrients that can fertilise aquatic vegetation.

To determine the status of the Hardy Inlet, preliminary studies in 1999 included the water quality sampling instigated by the Water and Rivers Commission (Hardcastle and Cousins 2000) and continued by the Department of Water 2006 and Forbes 2012 (Section 3.8). Another study of sediment quality included mapping of sediment grain size, organic content, heavy metals, pesticides, aquatic growth and nutrients, and preliminary experiments on nutrient movements between the sediment and water (Hale *et al*. 2000). These studies provided the framework for detailed surveys and experiments by Geoscience Australia (2007–2008) that examined conditions influencing nutrient movement between the sediments and water (Haese *et al*. 2010).

Sediments

In 1999 the types of sediments were generally similar to those reported in 1976 (Figure 3.1) although nutrients within the sediments had increased in some areas. Cores from the deeper reaches of the Blackwood River (BR2) and upper inlet channel near the Irwin Street boat ramp (HIIS) contained the finest sediments, while the coarsest sediments were collected near the estuary mouth, in shallow sand bars and the wharf area at Ellis Street. Concentrations of organic matter and organic carbon were generally highest in areas of fine sediment such as the Blackwood, although were uncharacteristically high in the Scott River site which had relatively coarse sediments.

Nutrient stores 1974 and 1999

In 1999 concentrations of nitrogen (TN) and phosphorus (TP) were higher at the organically enriched sites in West Bay (HI14) and Irwin Street, with the lowest concentrations at the mouth and in the channel areas. Comparison of samples collected in 1974 and 1999 (Table 3.1) revealed that nutrients and organic matter at sites in North Bay/Basin and to the west of Molloy Island had not changed markedly, but concentrations at Scott River had increased dramatically. The results indicate that, in the context of the high nutrient concentration in the Blackwood near Alexandra Bridge (BR2), more nutrients enter the Hardy from the catchments.

Although guideline concentrations for nutrients were not available in 1999, the highest concentrations in the Hardy were equivalent to and in some locations exceeded other acknowledged eutrophic systems in the south west such as the Peel-Harvey. With information that oxygen concentrations in the system had decreased since 1974, it was considered nutrients in the sediment could be released into the water column (Hale *et al*. 2000).

Other constituents of the sediments

In 1999, concentrations of pesticides (DDT and PUBs) and heavy metals (with the exception of arsenic) in sediments were below ANZECC (1999) guidelines and followed the pattern of organic matter (i.e. highest in the river and upper estuarine areas where sediments were finer). Arsenic was higher in West Bay and the adjacent upper inlet channel sites where concentrations exceeded ANZECC (1999) ISQG-L guidelines, but lower in the river sites. Nickel also exceeded guidelines in the Blackwood River near Alexandra Bridge and at Irwin Street. Pesticides were below detection limits. Concentrations of heavy metals that exceed guidelines are a concern and prompt the question: *What are or were the sources?* However presence of a heavy metal in cores begs further questioning: *Is it available for uptake, or is it inert and buried in the sediment or is the phosphorus in the system mediating release into the water column?* Clearly we need to know more about the distribution and concentrations of heavy metals and if they are inertly bound within the sediments, a factor mediated by conditions in the water.

Sediment nutrient stores in pore waters 2007

The 2007 survey of nutrient stores in the surface pore waters (spaces between the sediment particles) indicated that the dissolved inorganic carbon (DIC), total organic carbon (TOC), ammonium (NH_4^+), oxidised nitrogen (NOx), dissolved inorganic phosphate (DIP) (also referred to as orthophosphate (PO_4^{3-})), and silica (SiO_4^{4-}), varied greatly in different areas of Hardy Inlet (Map 3.2). Concentrations of DIC and nutrients did not correspond to those of the TOC. In West Bay (HD1), sediment DIC was low (22.4 mg/L), but TOC (5.1 wt%) was high. The reverse was found in the Blackwood River (HD9) with high DIC (73.5 MG/L) but low TOC (0.45 wt%). Low TOC was associated with sands of lower porosity. High TOC concentrations were associated with fine mud sediments of high porosity. The highest TOC (6.8 wt%) and highest porosity (89%) were recorded at the deepest site (7 m) in the channel north-west of Molloy Island (HD5) in 2007, which could suggest recent deposition of organic matter in fine sediments that led to high rates of decomposition and higher nutrients in the pore waters. The depth indicates that this site would have periodically experienced hypoxic and anoxic conditions. However, sandy sediment was found at the site in April 2008, indicating that the area was also subject to scouring. The hypothesis suggests that a combination of low oxygen and scouring would prevent the establishment of benthic fauna and limit bioirrigation of the organic-rich sediments allowing the nutrients to accumulate.

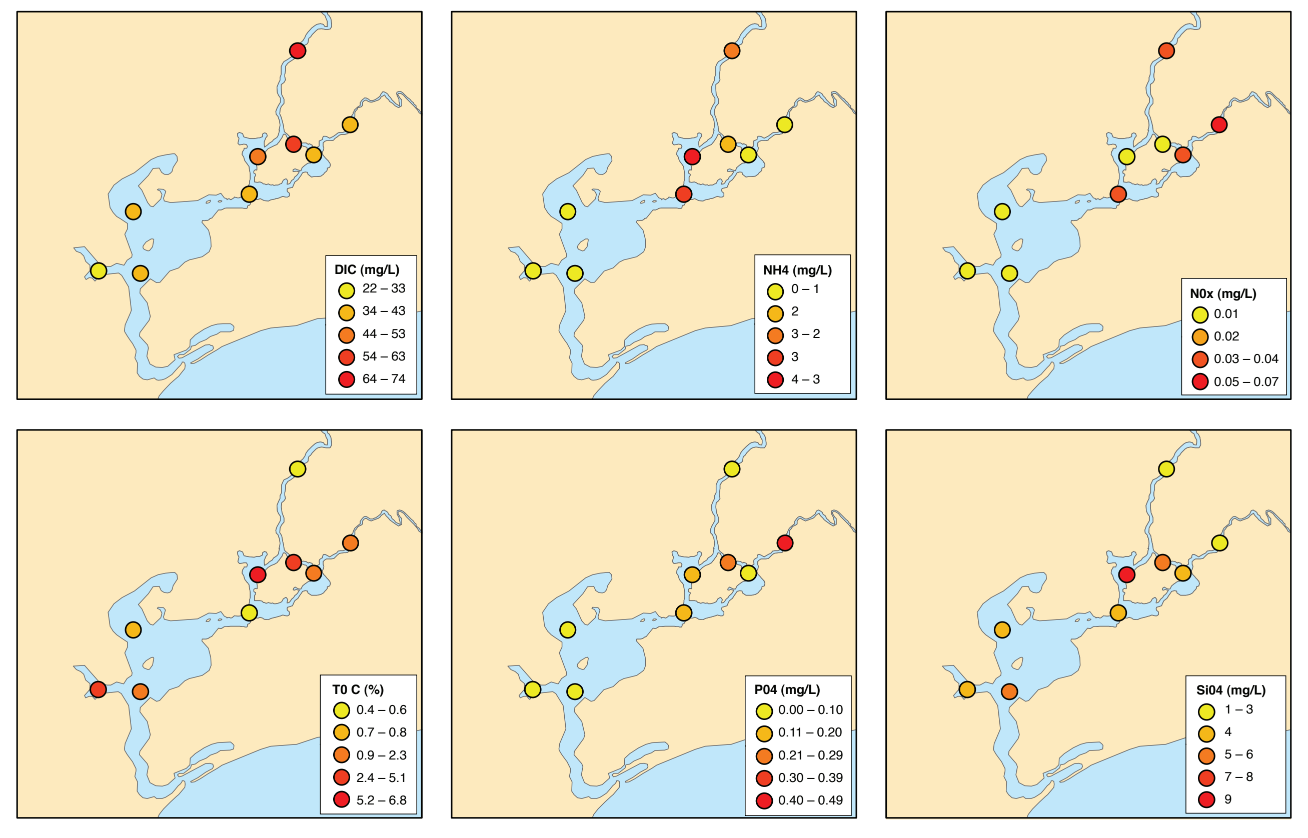
Generally, concentrations of carbon and other nutrients were highest around Molloy Island and lower estuarine reaches of the rivers. In contrast concentrations of NH_4^+ in West Bay, North Bay and the inlet channel (HD1, HD2 and HD3) were low and NOx and PO_4^{3-} lower than detectable limits.

Concentrations of nutrients in pore water at different depths in the sediment also varied. Profiles of the sediment indicated that ammonium (NH_4^+) concentrations were similar at most sites except for north-west of Molloy Island (HD5). This was much higher (0.52 mg/L) at 20 cm, and was the highest value recorded. Oxidised nitrogen concentrations were generally low except for high concentrations in the channel downstream from Molloy Island (HD6) and in the riverine area of the Blackwood (HD9).

These surveys indicated areas where sediment nutrients could be a problem and might be recycled into the water column. The surveys were in deeper water (>6 m) north east and west of Molloy Island (HD4A and HD5) and the Lower Blackwood (HD9) and Scott River. In these waters, which are subjected to stratification, low oxygen (hypoxia) and no oxygen (anoxia), and/or scouring that limits the benthic fauna, the sediments are more likely to accumulate nutrients. The site west of Molloy Island in seven metres of water had the largest pools of NH_4^+, PO_4^{3-}, SiO_4^{4-} — two to seven times greater than the other sites. With the exception of HD9 in the Blackwood, the other locations are characterised by fine sediment and the absence of oxygen facilitating release of nutrients into the overlying water.

Table 3.1 Nutrient in sediments 1974 and 1999. In Hale *et al*. 2000 units reported as mg kg^{-1}, in this document as identical Standard Units $\mu g\ g^{-1}$. Hale *et al*. 2000. Data 1974 from Congdon and McComb 1974.

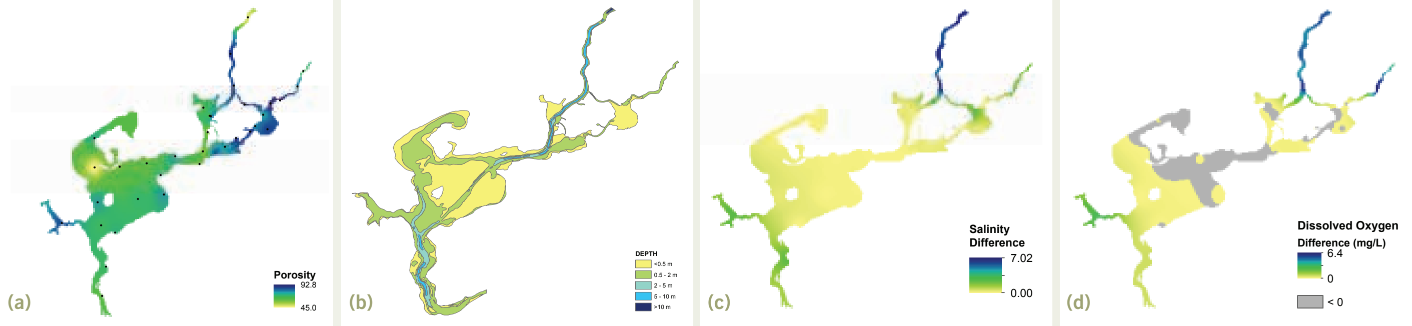
	Organic content ($\mu g\ g^{-1}$)		Total Phosphorus ($\mu g\ g^{-1}$)		Total Nitrogen ($\mu g\ g^{-1}$)	
	1974	1999	1974	1999	1974	1999
Scott River SR1	9.1	12.6	57	960	1410	5200
Basin/North Bay HI5	1.9	5.0	578	280	1960	1700
West Molloy Island HI8	3.2	2.0	144	140	2090	800



Map 3.2 Dissolved Inorganic Carbon (DIC), Total Organic Carbon TOC, and dissolved nutrients (NH_4^+, NOx, PO_4^{3-}, SiO_4^{4-}) held surface sediments Hardy Inlet September 2007. The sites in the lower estuary (HD1, HD2 and HD3) of West Bay, North Bay and the upper Inlet Channel had low concentrations of (NH_4^+, and NOx while PO_4^{3-}, was not detectable. In contrast, sites further upstream had the highest concentrations of carbon and dissolved nutrients. From Haese *et al*. 2010. Courtesy DoW.

The surveys thus indicated where experiments to examine nutrient cycling could be useful (Map 3.3).

Nutrient concentrations in water near the surface and bottom of the estuary provided additional information on the processes operating in the area. Ammonium (NH_4^+) concentration was generally low (0.02 mg/L) in surface and bottom waters, except for the sites in West Bays and the lower Blackwood (0.70 and 0.41 mg/L respectively), which were above the ANZECC trigger value (0.04 mg/L) for estuaries in south-western Australia. Concentrations of dissolved nitrogen oxides (NOx) were very low. Orthophosphate (PO_4^{3-}) was only detectable in the bottom waters of HD1 (0.013 mg/L) in West Bay and HD5 (0.007 mg/L) west of Molloy Island, but these were above the ANZECC value (0.005 mg/L). Silica (SiO_4^{4-}) was higher in bottom waters compared to surface waters at all sites, with the higher concentration in West Bay.



Map 3.3 Interpolated physical characteristics **(a)** Porosity, black dots show sampling sites **(b)** Water depth. Difference between bottom and surface water **(c)** Salinity and **(d)** Dissolved oxygen Haese *et al*. 2010. Courtesy DoW.

3.6 Sediment nutrient fluxes 1999 and 2007

Nutrient flux

Nutrient fluxes are measured to examine the potential for sediment to store or release nutrients i.e. if they are a sink or a source for nutrients. The chemical processes that determine how the nutrients react are influenced by the presence or absence or oxygen.

When oxygen is present (aerobic conditions), nitrogen in organic matter is mineralised by bacterial activity to ammonium through the process of **ammonification**. Ammonium (NH_4^+) is then converted to nitrate (NO_3^-) and nitrite (NO_2^-) in the process **nitrification**, which requires oxygen, and finally to nitrogen gas (N_2) during **denitrification**, which can occur with or without oxygen. Denitrification is particularly important as N_2 gas is not used by most plants and diffuses into the atmosphere. Ammonium and nitrite can also be converted to N_2 directly through another process called anamox.

In removing nitrogen from the water, these processes, and therefore oxygen, are crucial in reducing algal growth. In contrast, if oxygen gas is not available, nitrification and denitrification cannot proceed and ammonium builds up in the pore waters of the sediment. Similarly when oxygen is present, phosphorus in organic matter is converted to insoluble phosphate and is not available to plants. In the absence of oxygen, phosphate is released from the sediments where it is available for algal growth.

Oxygen is generally depleted when there is too much decomposing organic matter. Low oxygen also occurs during decomposition of organic material containing sulfur compounds, through sulfate reduction releasing 'bad egg gas' — hydrogen sulfide (H_2S).

Laboratory experiments 1999

In 1999, the capacity of the sediments in the estuary basin and lower Scott River to release nutrients was tested in the laboratory under aerobic and anaerobic conditions. The experiments were conducted over 96 hours with samples taken every 12 hours (Hale *et al*. 2000). The results indicated that nutrient release rates were lower than other estuaries in the south west. Phosphorus (PO_4) release was minimal under all conditions. Under aerobic conditions, phosphorus was probably taken up by sediment from site (HIS) in the upper basin i.e. the sediment was a 'sink' rather than a source of phosphorus. Ammonium (NH_4^+) release was an order of magnitude less than it was in the Peel-Harvey, a result perhaps not in accordance with the growing awareness about enrichment of the sediments. Unfortunately at the time little was known about the particular sites selected for these experiments, and they proved to be sites low in organic matter and nutrients, probably accounting for the lower than expected release rates, but indicating that similar experiments should be undertaken in West Bay and in the upper inlet channel were nutrients and organic matter were much higher. However, it took another 10 years for this to be done.

Benthic chamber incubations 2008

Benthic chambers are an experimental technique which were used to study fluxes within the estuary *in situ* at the sediment water interface. The chambers allow conditions to be controlled and nutrients collected from between the sediment grains and at the interface with the water column (see photograph page 44).

The experimental studies in 2008 focused on West Bay (HD1), the channel west of Molloy Island (HD5), deep holes in the Blackwood (HD9), and the lower reaches of the Scott River north-east of Molloy (HD4). These were stratified areas where saline water underlay the fresher river water and dissolved oxygen was low (Map 3.3c).

Oxygen was produced and DIC consumed during photosynthesis in the light chambers (Figure 3.7) located north east of Molloy Island (HD4) and west of Molloy Island (HD5). In contrast respiration, indicated by the decrease in oxygen and release of DIC, dominated in West Bay (HD1) and Blackwood (HD9).

Vehicle access to Molloy Island, April 2008. A. Brearley.

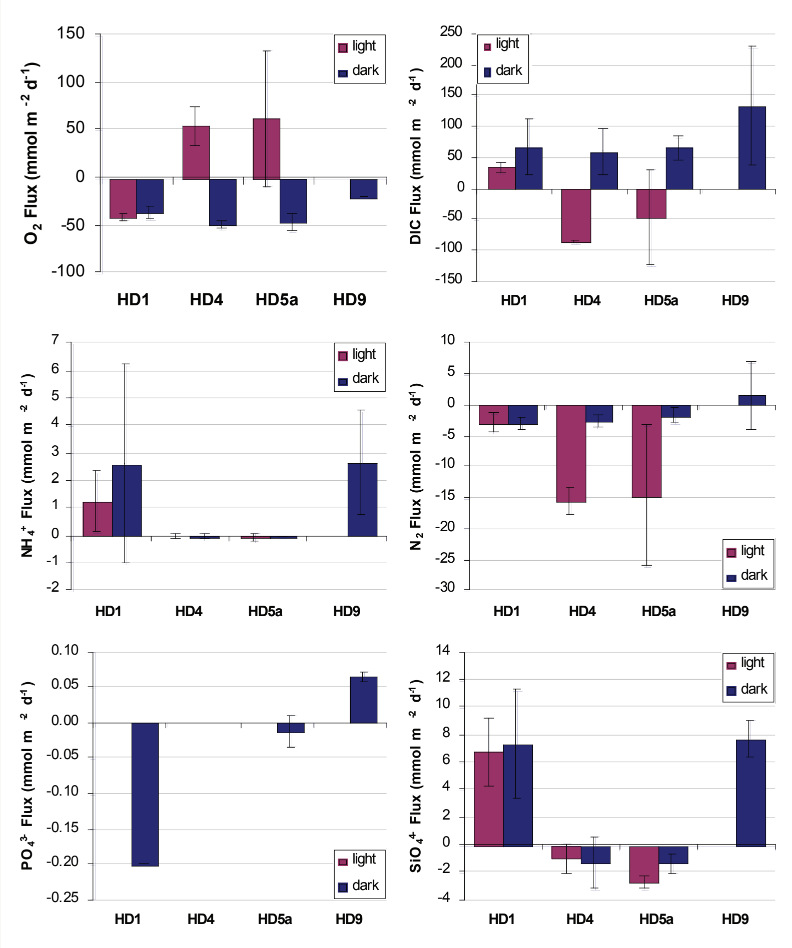


Figure 3.7 Fluxes of sediment nutrients in benthic chambers in the Hardy Inlet. Error bars represent standard deviation. Positive fluxes indicate release or production. In contrast negative fluxes indicate uptake or consumption. Haese *et al*. 2010. Courtesy DoW.

Ammonia flux reached 6.47 m mol m^{-2} day at HD1 and 3.98 m mol m^{-2} at HD 9. Nitrogen (N_2) was only released at HD 9. Nitrogen decreased in the other sites, indicating uptake of N_2. This is usually attributed to nitrogen fixation, possibly by cyanobacteria associated with the root zone of seagrass or growing epiphytically on seagrass leaves (Dudley *et al*. 2001 Kilminster and Garland 2009). Measurements of nitrogen uptake in the light chambers were considered erroneous as oxygen release can confound the results.

Fluxes of phosphorus (PO_4^{3-}) were only detected in the dark chambers with the only measurable concentrations found at HD 9 and HD1. At site HD1 the flux was negative suggesting uptake of phosphate into the sediment, which is unusual and unexplained. Silica (SiO_4^{4-}) fluxed from the sediment at HD1 and HD 9 and entered the sediment at HD4 and HD5.

Daily net fluxes that combine the results of the light photosynthetic response and the dark respiration provide an overview of the longer time frame that could influence processes in the water column. Sandy sediments in shallow water, i.e. HD5 and HD4 near Molloy Island, showed a photosynthetic response producing more oxygen and consuming more carbon in light over a 24-hour period. In contrast, at the shallow muddy site HD1 in West Bay and HD9 the deep sandy site in the Blackwood where respiration dominated, oxygen decreased and carbon (DIC) was released. However, slightly different conditions at each of the sites may account for the dominance of respiration. In West Bay, light and photosynthesis may be restricted by turbid conditions when the fine sediments are disturbed, whereas in the Blackwood with sandy sediments, light for photosynthesis is probably limited by depth. As the net fluxes (DIC, NH_4 and PO_4) in the Blackwood are unusually high, this may be indicative of aquifer discharge of nutrient rich water into the estuary. Differences in the sediment characteristics at HD9 identified in the 2007 and 2008 survey indicate that this site may be subject to scouring and that nutrient fluxes could vary dependent on the proportion of sand or mud.

Typically, the sediments of the Hardy are coarse and sandy with little organic matter, relatively low pore water nutrients. These nutrients are not generally released from the sediments. However nutrients in the water column support high rates of primary production, and light for photosynthesis is readily available in the shallow waters. In contrast, the deeper channel areas around Molloy Island and the lower Blackwood are more likely to experience stratification leading to hypoxia and anoxia. These areas may also be scoured during floods. This removes the fauna that facilitates nutrient loss through burrowing and bioirrigation. These areas remain a concern. Around Molloy Island and the junction of the Blackwood and Scott rivers, the low oxygen and higher nutrient release, despite the low concentration of organic matter, indicates that some other mechanism operates. This may be related to groundwater discharge associated with the housing development and high population within and surrounding the area.

Scenarios in the Hardy Inlet — useful indicators

Organic matter decomposition measured as benthic DIC flux and sediment phosphorus binding capacity, measured as phosphate flux under dark conditions (respiration) appear to be the most reliable measures of estuarine conditions. The rate of decomposition, which reflects the amount of organic matter, is also useful as it defines the trophic status of the system or the degree of eutrophication. However, further investigations to clarify these findings are planned.

Similarly the ability of sediments to retain phosphorus (which is dependent on oxygen) influences the amount available for the growth of aquatic vegetation, and the ratio of nitrogen to phosphorus, which determines which the type of aquatic growth. High phosphorus concentrations and therefore low N/P ratios, i.e. a relative paucity of N compared to P, favour the growth of toxic blue-green algal blooms.

The extent of the shallow sandy areas in the Hardy, indicates that nutrients released from the sediment are less likely to be a problem than in other estuaries with deeper basins, such as the Georges Basin in NSW and Wilson Inlet in WA.

3.7 Hydrology in the estuary

This section describes the hydrology of the estuary based on the 1974–1975 studies, which was during a period of regular high to average rainfall and river flow. The studies set the scene for understanding the Hardy today in terms of stratification and mixing and the resulting salinity, temperature and oxygen dynamics. These findings are followed by a summary of small studies in the tidal river (2003 and 2006) that provide a contemporary view of the system where river flow has decreased, and provide a base for future projections of the hydrodynamics. As this document presents a history of hydrological studies in the Hardy salinity is reported as ppt (parts per thousand), although salinity is now considered to be a parameter without units e.g. seawater of 35 ppt or ‰ is expressed as 35.

Relative to the size of the combined catchment of the Blackwood and the smaller Scott, the estuary area (9 km^2) is much smaller than many others on the south coast, such as Wilson and Broke (48 km^2) and Walpole-Nornalup (15 km^2), and is relatively shallow. The tidal river section (55 km) is however considerably longer than that of any other river in the south west except the Swan (60 km).

The competing roles of river and tidal flows and the subsequent stratification along the estuary of the Blackwood, has long been recognised. The 1970s studies aimed to understand these dynamics throughout the year. Thus the investigations of seasonal changes required observations throughout the year and those on tidal dynamics were more intensive over short time periods (Imberger *et al*. 1976 and Hodgkin 1978).

In summary, the water movements and hydrological conditions were considered to be due to the interaction of a number of forces. First, the varying volume of fresh, low density water entering from the river; second, density differences between fresh water and sea water; third, tide and other changes of sea level causing an oscillatory action; fourth, turbulent mixing in shallow water (mainly due to wind) and at the interface between different water bodies.

River and tidal flows — three states 1974–1975

The study in 1974–1975 documented three states dependent on river flow and tidal flows: Winter condition, salt wedge and summer condition (Figure 3.8).

- **Winter condition** was defined as when daily river flow exceeded 20 x 10^{6}m^3 (20 GL) and impeded tidal flows so that the entry of marine water was limited and the estuary was fresh throughout for about 6-8 weeks (10% of the year) (Figure 3.8c and Fig 3.9). With this flow the whole volume of the estuary was replaced with fresh water in two days. Although the term ‘winter’ was used to describe the fresh water state that followed the pattern of ‘normal’ rainfall seasonality, it was noted that flushing could occur at any time when river flows were high or not at all when rainfall was low, in which case the full winter state was unlikely to develop. In this winter condition ‘*the estuary can only be regarded as estuarine in the crudest geographical sense; it is a fast flowing river with a considerable head of water in the upper estuary*’.

  Flow was predominantly from the Blackwood, with the Scott contributing only 5–10% of the total. The two water bodies were of quite different colour and only blurred by turbulent mixing between Molloy Island and the basin. Even there, the Scott water moved down the eastern margin, while the Blackwood water flowed over the northern and central part of the basin.

  In the basin, flow velocities (50–80 cm/sec) were highest in the channels and lower over shallow areas (20 cm/sec) and even slower in North and West Bays. The highest flow rates (100 cm/sec) were measured at the mouth.

- As the river flow current declined and was not strong enough to prevent the tidal inflow, dense seawater moved upstream on a flood tide beneath the out-flowing less dense fresh water forming a **Salt Wedge** in the inlet channel (Figure 3.8c, 9/6/74). This produced a two-layered or stratified structure in which the two water bodies retained their identity, with the boundary between the fresh and salt water termed the halocline. Initially the salt wedge was located in the inlet channel but gradually, with the decline in river flow, moved upstream into the tidal river and the estuary (Figure 3.8d, 20/10/74). The ebb and flow resulted in mixing of the water, a gradual upstream propagation of saline water and an increase in salinity throughout the system.

- Finally, with river water flow less than 0.25 x 10^{6}m^3 per day (0.25 GL) there was little effect on the dynamics of the estuary and the inlet was essentially marine with salinity about 30 ppt. Although the upper river reaches were highly stratified, the system was in the **Summer Condition** (Figure 3.8a (11/4/74) and Figure 3.9). At this time the estuary was dominated by tides that moved up and down the estuary. In 1975 the summer condition was probably established by late January.

  Tidal flow movements were tracked by dye releases in February 1975 when water levels were about 25 cm lower and much of the delta was barely covered with water. They indicated flow in the basin was restricted to the dredged channel with a maximum rate of 0.55 m/sec. Upstream of the basin, off Island Point, the maximum flow rate was only 0.15 m/sec. Only at the mouth were tidal current speeds similar to those observed during winter flow conditions, a maximum of 80 cm/sec. Although the tidal currents were slow, they did move a considerable volume of water, and when coupled with the small volume of the basin and inlet, resulted in a considerable exchange of water with the ocean. Despite these currents in the absence of strong longshore oceanic current or other mixing, much of the estuary water which left the estuary on a falling tide would have returned on the next rising tide.

- With the onset of rain and river flow in autumn, fresh water flowed over the saline water and stratification was re-established, particularly over deeper areas of the tidal river, before the winter condition was again fully established.

Temperature

Records from 1974–1975 illustrate that seasonal water temperature range, 28°C in February and 10°C in June–July at Station 90 between the basin and Molloy Island, was much greater in the estuary than in the ocean, and solar radiation influenced the temperature in the shallow basin. In summer, saline water below the halocline, about two metres upstream of Alexandra Bridge, was warmer (28°C) than the surface water (20°C) and temperatures increased upstream. The lower temperature of the surface waters was attributed to the solar heating during the day and evaporative cooling at night. Solar radiation also led to heating of the upper part of the saline deep water, which was moved upstream by tidal flows with heat increasing at the head of the estuary. The persistence of higher temperatures in the deep water was attributed to limited mixing across the halocline.

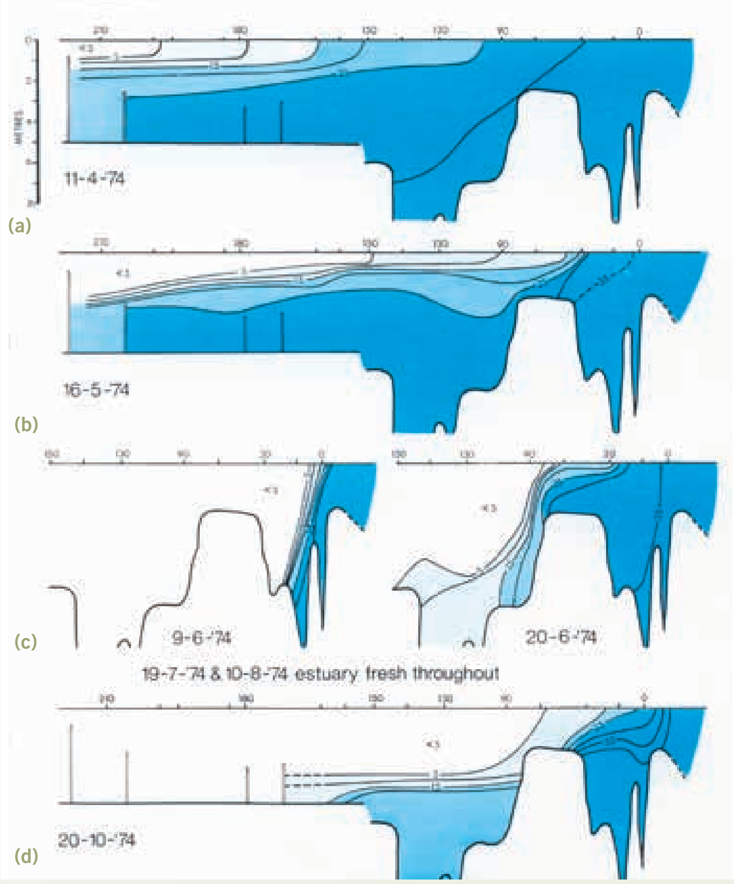


Figure 3.8 Salinity profiles to show seasonal hydrological change in the Hardy Inlet. Station numbers at the top from the ocean mouth (Stn 0) right to Warner Glen Bridge (Stn 210) left), (Map 3.1a): **(a)** (11/4/74) shows late summer conditions; marine water has penetrated upriver almost as far as Warner Glen Bridge with some fresh water at the surface. **(b)** In May (16/5/74) increased flow has moved fresh water downstream. **(c)** In June (20/6/74) fresh water had penetrated most of the inlet, marine waters are excluded and isohalines at the mouth are almost at vertical — winter condition. **(d)** In October (20/10/74) flow has decreased and saline marine water is again penetrating along the bottom of the inlet. Different densities of fresh and salt water produce a two-layered structure in which the two water bodies tend to retain their identity, i.e. it is stratified. The bottom waters below the halocline may become deoxygenated in the tidal river in summer. Source: Hodgkin, 1978.

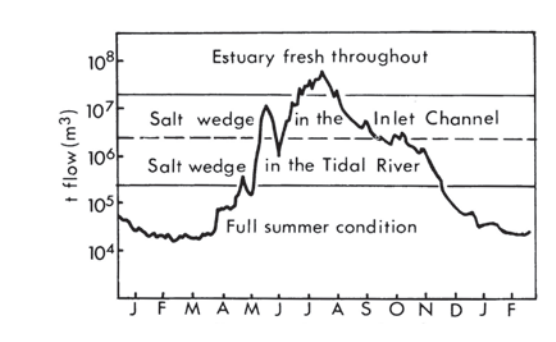
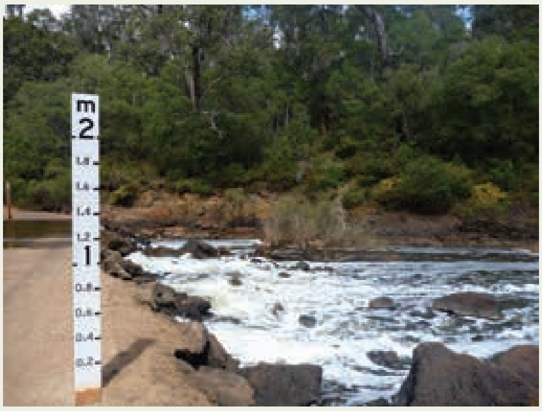


Figure 3.9 Total flow per day entering the head of the estuary at Warner Glen Bridge 1974–1975 and status of the estuary (Hodgkin 1978 adapted from Imberger *et al*. 1976). Horizontal lines show the transition levels of the dynamical regimes. Volume determined as 41.5 times flow measured at Rosa Brook gauging station, which was operational from July 1968 to March 1979 and reopened in 2003.



Hut Pool, October 2010. A. Brearley.

Oxygen

The oxygen concentration of flowing river water is usually high through contact with the atmosphere. In contrast, saline water along the bottom is isolated and oxygen declines as plants respire and organic matter is decomposed. Low oxygen conditions are unfavourable for aquatic life, particularly fish, and conducive to chemical processes that release nutrients from the sediment, which in turn fertilise algal blooms. Stratified conditions that favour deoxygenation are therefore usually regarded as a symptom of poor estuarine health.

Early records of oxygen status in the Blackwood are limited, however sampling by CSIRO Fisheries and Oceanography at Alexandra Bridge documented deoxygenation only in summer below the halocline in the 1952–1954 period (Rochford and Spencer 1952–1954). Similarly Hodgkin recorded deoxygenation below the halocline at three metres at two sites upstream of Alexandra Bridge in January 1975. When the Water and Rivers Commission, now Department of Water, started regular water sampling in 1999, the lowest oxygen concentrations (3% saturation) were recorded in summer near the river bottom at Alexandra Bridge (Hardcastle and Cousins 2000), a continuing issue in that area of the estuary.

Tides and changes in water level

The changes in water level due to astronomic tides in south-western Australia are small and are classed as ‘microtidal’, generally with only one high and one low tide per day (i.e. diurnal). However more extreme changes, higher highs and lower lows, than those predicted have been of interest to marine scientists for many years and subject to more intensive research in recent years with the debate about changes in global sea level. Non-tidal factors include winds, air pressure (barometric meteorological), storm surge, continental shelf waves and river flow. These factors vary seasonally and over decades (Table 3.2).

Changes in water level within an estuary and river are much smaller than in the ocean. They also decrease upstream and lag behind the oceanic changes. Investigations in 1974–1975 showed the change in water level within the estuary at Seine Bay was 70% less than in the ocean seaward of the bar, with a delay of one to two hours. At Alexandra Bridge, changes were 40% of those in the ocean and

Table 3.2 Tides and other factors influencing sea level in south west Australia. Courtesy C. Pattiaratchi

Cause	Height (cm)	Variability and time scale
Tides	50	± 10 cm? 20 cm once per day. Nodal cycle 18.6 years
Storm surge	50-80	Increase in frequency projected
Seasonal winter higher	20	± 10 cm Leeuwin Current
Inter–annual El Nino/La Nina	20	± 10 cm increase year to year variability since the 1970s
Mean sea level increase	15	Increase in last century

Sea level due to combined effects can result in a range of two metres. Changes in last 30 years (Haigh *et al*. 2000). Tides follow a nodal cycle of 18.6 years with last peak in 2007 and the next peak in 2025. Due to this cycle the effect of the projected increase in sea level may not evident until 2025. Note the increased sea level with strong Leeuwin Current in winter versus low atmospheric pressure and higher sea level.

were delayed by about 3.5 hours. Differences due to astronomic tides in the 1970s had a maximum range of 70 cm, however the most extreme change in water level due to non-tidal factors measured at Point Irwin was 1.3 m. Effects of atmospheric pressure associated with tropical cyclone Vanessa in January 1976 were also recorded when the rock bar at the estuary head in the Scott River was submerged.

Under high river flow in winter, tidal changes were not obvious and water level rose in the tidal river. In early August 1974, water was more than six metres above normal summer level at Warner Glen Bridge. During the 1964 floods, water covered the handrails at Warmer Glen and at Alexandra Bridge rose to the roadway. In 1982 floods associated with cyclone Bruno flooded roadways around Nannup, delivering more than 60% of the annual flow in six days in January.

The difference in the duration of the rising (flood) tide relative to the falling (ebb) tide (asymmetry) also has effects on current strength.

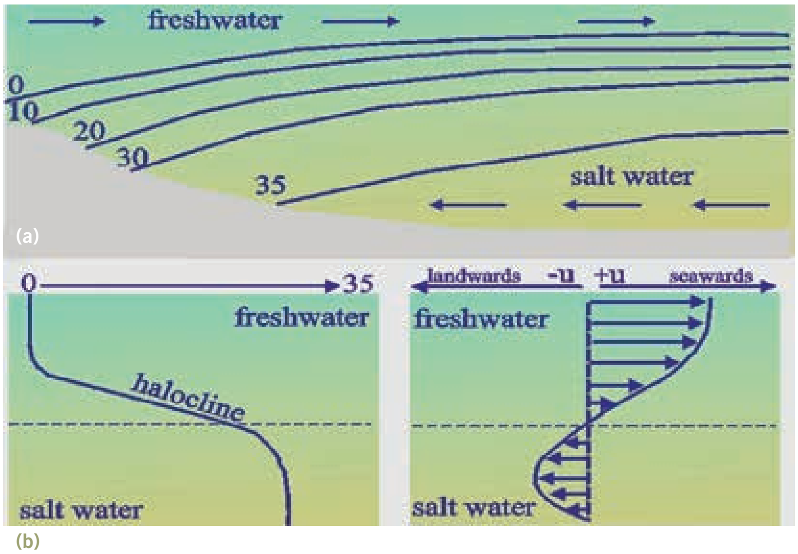


Figure 3.10 Characteristics of water flow and circulation in an estuary. **(a) Top**: Freshwater as a buoyant plume flowing seawards over saline water, which is flowing landwards due to sea level changes in the ocean. **(b) Bottom left**: Halocline defines the boundary or zone change from freshwater at the surface and saline water at the bottom. **(b) Bottom right**: Freshwater flows are faster due to the slope of the river surface relative to the estuary and low density. Salt water inflows from the ocean are slower due to bottom friction and differences in salinity create stresses which result in turbulence and mixing. Courtesy C. Pattiaratchi.

When the ebb tide is longer than the flood tide, the flood tide is stronger and the system is referred to as flood dominated. In contrast a system is ebb-dominated with strong outgoing currents when the falling tide is shorter than the rising tide. This flood/ebb dominance of a particular system can now be determined from oceanic tidal elevations, which are more readily available than actual data on a particular estuary such as the Hardy. Tidal velocity asymmetry is of particular interest in south western Australian estuaries as it influences the net sediment transport out of and in to a system, and the long-term erosion and accretion within a system (Ranasinghe and Pattiaratchi 2000).

Stratification and mixing

In any estuary the movement of water upstream is also influenced by constriction or narrowing of the channel, large shallow areas and sand banks, density and stratification of the water body. In particular, the density differences along the estuary (freshwater to seawater) results in a net seaward flow at the surface and a net bottom landward flow of seawater which is defined as the gravitational circulation (Figure 3.10).

Persistence of layering or stratification within the water column depends on the relative strengths of factors that favour stratification versus those that favour mixing, including rainfall, river flow, tidal forces and wind mixing. Generally for wind mixing, speeds greater than 11 m per second or 40 km per hour are required, with the effect confounded by the shape of the water body and exposure to the prevailing wind. Hodgkin suggested that unlike the case of 1974 when the system was flushed completely, in most years river flows would be inadequate to exclude the salt wedge and that this transitional stratified condition persisted in most years. Furthermore in years of very low river discharge, although the shallow basin might be fresh for a period every winter, a deep salt wedge might persist in the tidal river. Flow to completely flush the system was calculated in 1978 as 20 GL a day over two days (Imberger *et al*. 1974). Although flows recorded at Hut Pool have in the last decade seldom reached this magnitude, inflow from the Scott and Chapman also contribute to the daily flows. Declining river flow is of great concern and the location of the saline front and stratification is of particular interest in terms of documenting change and health of the system.

Urban landscape Augusta, April 2008. Houses, trees and rushes lining banks of the estuary. A. Brearley.

Refining the balance of river and tidal flows 2000–2006

While exceptionally high flow in 1974–1975 reduced the salinity dramatically for many months, the current conditions of declining rainfall and river flow present a number of different factors that have not as yet been investigated in the same detail. However, a wider appreciation of marine–freshwater exchange in other South West estuaries due to tidal and non-tidal changes in water level, and investigations of the system by students (Hunt 2003 and Le Souëf 2006) together with computer modelling under the direction of The University of Western Australia oceanographer Professor Charitha Pattiaratchi, provide some insight into current conditions. These studies, unlike those in 1974, were of short duration (≈ one month) and focused on the extent of saltwater intrusion and stratification in the lower channel of the Blackwood River.

Tidal river Molloy Island to Alexandra Bridge 2001–2003

The study by Hunt (2003) was located between Molloy Island and Alexandra Bridge. Conductivity (salinity), temperature and depth (as pressure) were measured with a CTD meter at 11 sites and an Acoustic Doppler Current Profiler (ACDP) deployed for 22 days in autumn (18 April to 10 May 2001) approximately three kilometres upstream of the Molloy-Blackwood junction. An ACDP emits acoustic beams that are scattered by small particles of sediment and zooplankton that move with the currents, and the reflected beams measured by the sensor are resolved into three-dimensional currents. In addition, a digitised bathymetric map of the river bed, from the mouth to Warner Glen Bridge was developed for use in modelling the effects of different current flows and stratification.

River flow during the study was very low, but in early May increased rapidly over three days to 0.18 x $10^6 m^3$ per day. This was however well below the rate of 0.25 x $10^6 m^3$day per day (0.25 GL) used by Imberger *et al*. (1976) to define summer or stratified conditions and indicated that the estuary was in the ‘summer phase’ during the investigation. Although 2001 was a particularly dry year, flows since 1983 have seldom reached the threshold for the winter condition (20 GL day) indicating that in most years the estuary oscillated between the summer and salt wedge (transition) condition.

Temperature and salinity profiles in 2001 were similar to those of 1974–1975. Temperature was higher in the deeper areas and increased upstream. Maximum temperatures were closer to the surface upstream with all sites peaking at depths of one to four metres.

Salinity was highest (31 ppt) at the downstream site, and lowest (15.5 ppt) in the surface water at Alexandra Bridge. Salinity was also higher with increasing depth, with a sharp halocline between one and two metres where there was an increase in salinity of up to 12 ppt over one metre. Below two metres salinity was 28 to 31 ppt. Salinity was also high in lower reaches of the tidal river where water was deeper and the bathymetry more complex. The low salinity surface water probably corresponded to the river discharge five days before sampling, which was insufficient to decrease salinity in the deeper lower channel.

Dissolved oxygen concentrations (DO) generally decreased upstream and with depth. Although the highest concentration of oxygen (9 mg/L) was at the surface near Alexandra Bridge, below the halocline, at 1.5 m, oxygen was low (2 mg/L) and attributed to a lack of mixing. In contrast, the higher concentration of oxygen in the lower Blackwood was attributed to an increase of mixing, predominantly by tides. However, even there oxygen concentrations below 5 mg/L were recorded. Although there were no comparative measurements of oxygen in 1974, these results in combination with high salinity and temperature stratification indicate that the halocline was shallower and the extent of well-oxygenated water reduced.

Currents measured with the ACDP generally followed the pattern observed in 1974–1975, however the low flow conditions in 2001 highlighted the dominance of tides during periods of low river discharge. The tidal cycle was more evident near the riverbed than near the surface where the current may be influenced by other factors. Flood tides appeared to be dominant particularly near the surface. There was a lag time between surface and bottom of almost five hours (four hours 42 minutes), possibly due to bottom friction and local bathymetry. As a result the bottom flow was reversing before the surface flow, so that surface and near bed currents were flowing in opposite directions, particularly close to times of reversal of tidal flow (i.e. close to high and low water).

While the 1970s study focused on the importance of river flow as a driver of seasonal circulation in the estuary, the study in autumn 2001 demonstrated that the system was now experiencing periods of low flow more typical of a summer state with tides as the dominant factor. Therefore with the projections of lower river flows, tidal influences may be increasingly important in determining conditions in the estuary.

Tidal river upstream of Alexandra Bridge 2006

Building on the previous study, Le Souëf (2006) investigated the region immediately upstream of that studied by Hunt (2003). Field data on salinity and temperature were collected (17 June and 1 July 2006) at 19 sites about 0.5 km apart from Alexandra Bridge to the rock bar upstream of Warner Glen Bridge, including one site in the Chapman River. A CTD sensor was deployed to measure conductivity (salinity), temperature and depth in the river near Alexandra Bridge in the deepest section of the main channel (5.5 m) where tidal variation in water level, salinity and temperature were likely to be significant. Field data were used to validate the modelling of river flows required to flush the estuary and to define areas likely to experience stratification and anoxia.

Modelling was based on Hunt's (2003) bathymetric map from the estuary mouth at Augusta to Warner Glen and modified with grid squares reduced to 50 m x 50 m. River flow was based on 1983 to 2005 data from Hut Pool gauging station using three scenarios: Average flow of 4.8 GL day, maximum flow 17.5 GL day, and no flow, and the influence of tides and a combination of tide and surge.

Despite the low rainfall and below average river flows, measurement of fresh water flow over the more saline water allowed comparison with data collected in 1973–1975. It also contributed to calibration of the model, and modelling of different volumes of river discharge and changes in the flushing and mixing dynamics.

The effects of storm and low air pressure were detected in water level data at Alexandra Bridge in late June. Disturbance of the tidal variations in temperature and salinity also illustrated that mixing throughout the water column occurred during the storm, possibly due to disruption of the tidal cycle and upstream movement of saline water.

The two samplings showed development of salinity stratification over the two weeks of the study, and the effect on the isolation and deoxygenation of the bottom water (Figure 3.11).

Dissolved oxygen followed the salinity profile, with average concentrations of 7.6 mg/L at the surface and 4.1 mg/L at the bottom on 17 June, and 8 mg/L (surface) and 5.5 mg/L (bottom) on 1 July, with average surface and bottom saturation of 78% and 56% respectively. Salinity was particularly high, three times the surface salinity, in a 10 m deep hole upstream of Warner Glen compared to the adjacent shallower areas. Oxygen concentration was also low at less than 1 mg/L and saturation less than 10%.

An extensive patch of high salinity (25 ppt) and low oxygen (≈0 mg/L and 30% saturation) water was also recorded 5.5–8 km upstream of Alexandra Bridge. Another eight patches of strongly stratified water, where river bed salinity of 30 ppt and oxygen 30% saturation, and surface salinity 8 ppt and oxygen 8 mg/L (greater than 70% saturated), were also recorded in the same area. When coupled with the shallow halocline reported by Hunt in 2003 when river flow was low, these results indicate that the extent of low oxygen habitat is likely to be extensive and well oxygenated quality habitat suitable for fish is now restricted.

The model and field measurements in 2006 corresponded with each other and fit the expectation of changes in salinity with tides. During the ebb tide, salinity at the entrance decreased and fresh water moved downstream reaching a minimum at low tide. The flood tide brought an increase in salinity equivalent to that of seawater. The salinity changes illustrated that stratification increased over the tidal cycle indicative of tidal straining where the surface water moves faster than the bottom water due to shear forces. Maximum stratification at late ebb tide and minimum stratification at late flood tide, and the slope of the salinity profile towards the ocean, correspond with ebb tides and tidal straining in other estuaries. The low river flows during the study illustrate the effect of river flow on the upstream tidal flows, with the salt wedge detected eight kilometres upstream of Alexandra Bridge with salinity ranging from 15 to 25 ppt over two metres. Generally salinity was low, about 2 ppt at the surface at most sites upstream of 8–14 km and bottom salinity approaching 30 ppt.

The 'tide and surge' model indicated that with high surge there was a net movement of seawater into the estuary, with low surge net movement from the estuary to the ocean, both of which influence the estuary salt balance. Thus non-tidal effects could disrupt the regular effect of tides and conditions favouring stratification and therefore low oxygen.

Calculations by Imberger *et al*. (1976) indicated that 20 GL/day (two days) was required to flush the estuary with fresh water.

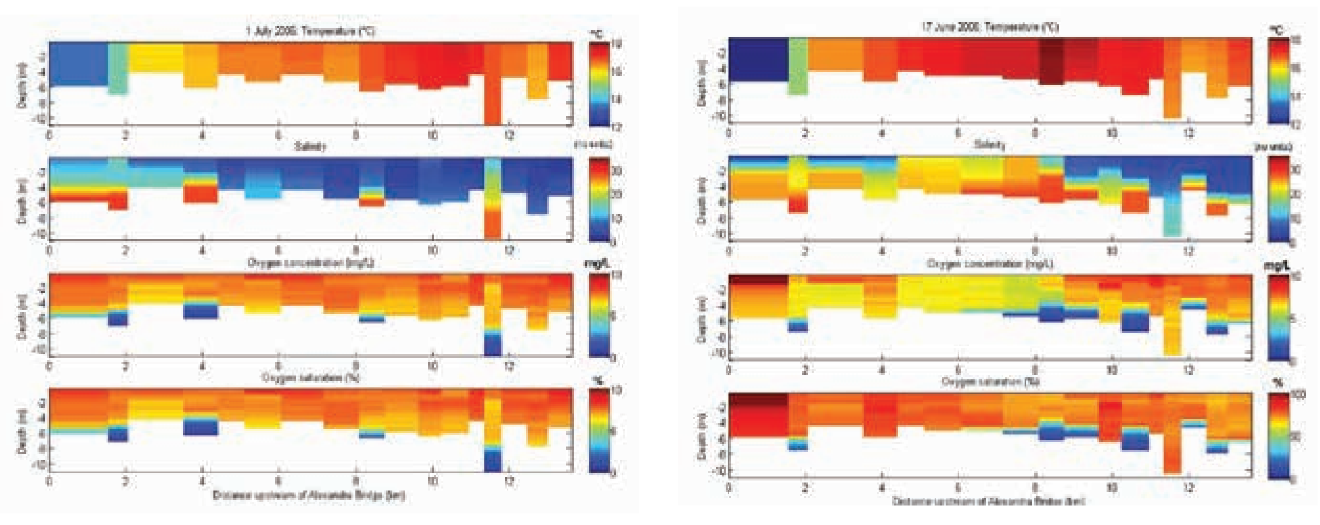


Figure 3.11 Changes in temperature, salinity and oxygen concentration and oxygen saturation in the Blackwood River Alexandra Bridge to rock bar at Warner Glen 17 June and 1 July 2006. Adapted from Le Souëf (2006), courtesy C. Pattiaratchi 2011.

Table 3.3 Modelled flushing times representative of flow conditions. Adapted from Le Souëf 2006.

River flow rate (GL/day)	Flushing time	Condition
0.009	92 days	Low summer flow
4.8	1.3 days	Average winter flow
17.7	8.5 hours	High winter flow

However modelling in this study indicated that much lower river flow of 4.8 GL/day for 24 days could flush the estuary and negate the effect of seawater intrusion. Flushing time was calculated at 92 days during summer (Table 3.3). This summer flushing time is low compared to many estuaries that are flushed in 10 days, but in the same order as Wilson Inlet (Ranasinghe and Pattiaratchi 1998). Flushing could also occur with lower flow over a longer time period. Flushing times are likely to represent the effect of estuary shape and highlight a direction for further research.

The model also allowed preliminary calculation of the relative contribution of the stratification and mixing processes (Table 3.4). Although to be viewed with caution, these results indicate that, gravitational circulation was more important than tidal straining in influencing stratification. As proposed by Imberger *et al*. 1976 and Hodgkin 1978, unless more than 40 km/hour, wind is unlikely to influence mixing in the deeper riverine areas of the Blackwood.

The correspondence of field data and model results confirms that further development of models will be a useful tool for predicting the estuary under the conditions expected with different river and tidal flows. The decrease in river flow and increase in marine intrusion since the 1970s appears to increase stratification and enhance conditions favouring low oxygen. This in turn decreases the habitable environment for biota requiring high oxygen and increases the likelihood of nutrient release from the sediment and phytoplankton blooms.

Table 3.4 Magnitude of stratifying and mixing terms. Source Table 4.3 from Le Souëf 2006.

	Potential energy anomaly term	Magnitude ($Jm^{-3}s^{-1}$)
Stratifying	Gravitational circulation $(d\Phi/dt)_G$	7×10^{-5}
	Tidal straining $(d\Phi/dt)_S$	2×10^{-5}
Mixing	Tidal mixing $(d\Phi/dt)_T$	2×10^{-5}
	Wind mixing $(d\Phi/dt)_W$	2×10^{-5} - 1×10^{-3}

NOTE: Average wind speed at Cape Leeuwin is 25 km/hr (2×10^{-5} $Jm^{-3}s^{-1}$) with gusts to 120 km/hr (1×10^{-3} $Jm^{-3}s^{-1}$).

Currently the effects of tides and the inflow of marine water could be influenced by two processes, the decline in river flow allowing an increase in the upstream tidal movement, and the more circuitous path along the old channel of the Deadwater decreasing tidal exchange. Public opinion favours the idea that less tidal flushing is a primary issue and that movement due to tides is less obvious with the eastern opening. However tidal exchange is actually quite considerable for a longer period, as the estuary has become more saline and marine debris clearly enter as drift. The major change over recent years has been the low fresh river flows in recent decades.

3.8 Assessing water quality in the estuary — nutrients

This section describes the interactions between the nutrient loads from the catchment river flows, tides and conditions in the Hardy Inlet that influence water quality in the estuary.

The increase in nutrients entering from the catchment over the last 40 years is quite clear. The Scott catchment contributes the largest phosphorus load (Table 3.5), which accumulates at the confluence of the river channel with the Molloy basin (Section 2.4 and 2.5). In contrast the Blackwood contributes the highest nitrogen load.

Surveys by Geoscience Australia indicate that soluble forms of nitrogen and phosphorus (ammonium and orthophosphate) are already held in the sediments and are recycling into the water column (Section 3.6). The increase in algal blooms and change in the types of algae, particularly the unwanted species, are also evidence that the system is changing.

Table 3.5 Nutrient loads (tonnes) of TN and TP in summer (December to February) and winter (June to August). Source Forbes 2013 DoW.

	Blackwood River		Scott River	
	TN	TP	TN	TP
Summer 2008–2009	3.0	0.1	3.7	0.6
Winter 2009	794	14.3	113	16.4

Salinity and oxygen in the estuary

The previous sections of this chapter described the hydrology of the estuary and the balance of outward flowing fresh river water and tides that bring marine water upstream. The decreased river flows and subsequent larger tidal flows have resulted in a more saline state, and extensive and persistent stratification accompanied by a decrease in the area of oxygenated water.

Due to wind mixing in the extensive shallow areas of the Hardy Inlet, there is little difference in salinity (only 5 ppt) between the surface and bottom waters (Figure 3.12). However upstream around Molloy Island and in the tidal Blackwood River wind mixing is limited, and the differences between the fresher surface water and deeper saline water are more pronounced. The deepest water may be hypersaline (45 ppt) with differences between surface and bottom as high as 25 ppt.

Differences in salinity and dissolved oxygen between the surface and bottom follow a similar pattern with the greatest differences in obvious upstream areas (Figure 3.12b). Here oxygen may be less than the critical values of 2 mg/L. In the main body of the estuary the waters are not only mixed but oxygen concentrations are generally higher throughout. At about 6 mg/L they are suitable for aquatic fauna. Low concentrations of oxygen generally correspond with isolated areas of saline water in the deepest areas where organic matter accumulates and bacterial decomposition removes oxygen. Flushing of these waters occurs only during persistent high river flows, which do not occur every year. Compared to the 1970s, the salinity stratification and low oxygen conditions are more widespread and persist for much longer.

So the question is, *does it matter if the system is more saline, the water body stratified, and oxygen low?* The answer is yes. More saline water affects the types of animals and plants in the water and around the edges, and high oxygen concentrations are essential for many organisms although some mobile types may be able to move away. More importantly, low oxygen triggers undesirable chemical processes, most notably the release of nutrients stored in the sediment that fertilise algal growth, particularly 'less desirable' species of phytoplankton.

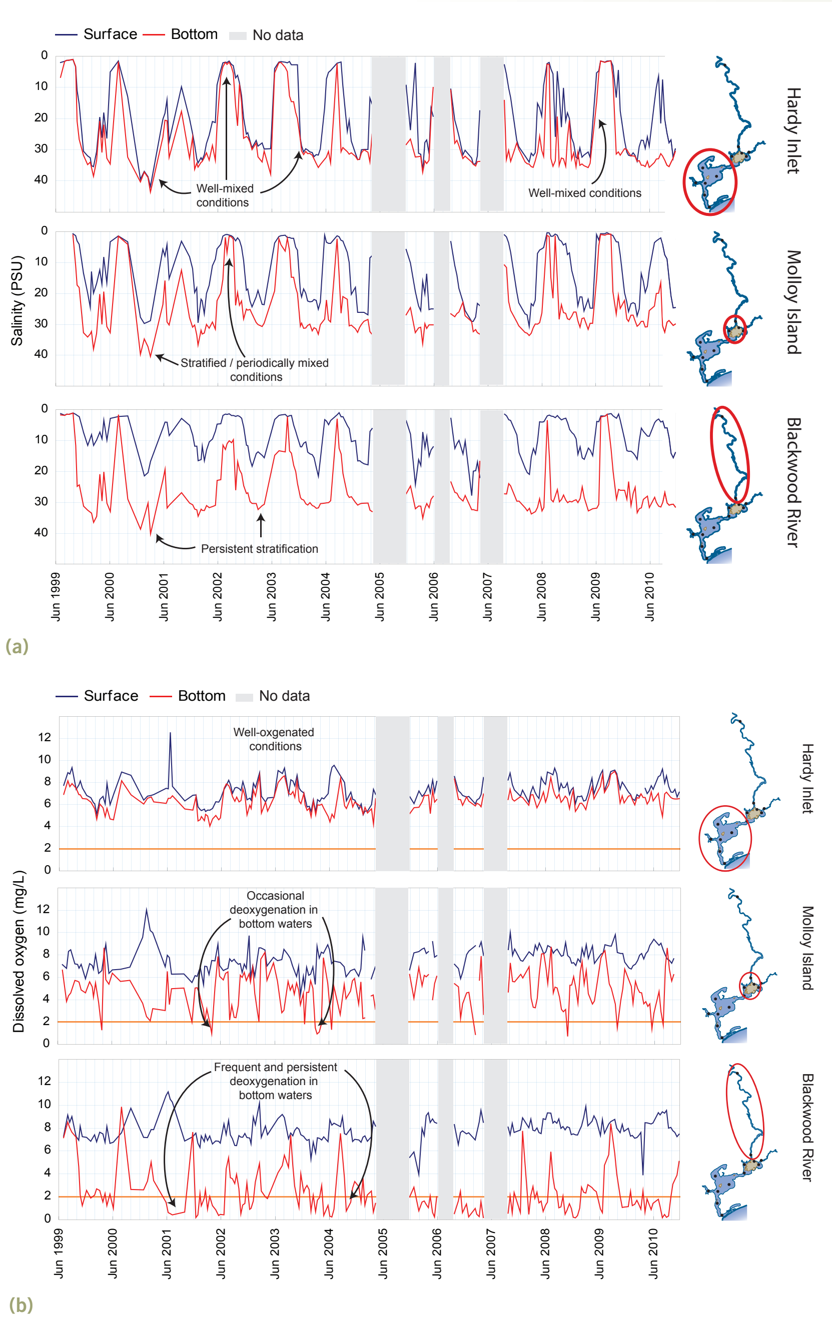


Figure 3.12 Salinity and oxygen concentrations in the tidal areas of the Blackwood River, Molloy Island and Hardy Inlet (1999–2010) Red line bottom, and blue line surface. ANZECC/ARMCANZ guideline value for oxygen indicated by a straight red line at 2 mg/L.

Ex Hardy Inlet Condition, courtesy V. Forbes DoW.

Nutrients — from the catchment and response to stratification

Nutrient concentrations in the estuary waters are influenced by rainfall, river flow, and stratification and low oxygen in the estuary. These changes are revealed through variations in nutrient concentrations throughout the year, and in different depths of the water column and areas of the system. To obtain this information, water samples were collected every two weeks throughout the estuary for analysis of nutrients and water chemistry (salinity, temperature, oxygen). The sites correspond to the original 1970s sites and include two sites in the tidal region of the Blackwood River (at Alexandra Bridge and near the confluence with the Hardy Inlet), one site in the estuarine area of the lower Scott and at nine stations along the length of the Hardy Inlet (Figure 3.1). This monitoring ceased in 2011–2012.

Nutrients are transported to the estuary in river water, which generally flows across the surface of the more brackish or saline water brought by tides. Between June and September when flow is highest, concentrations of TN and TP are also high (Figure 3.13). In general concentrations of TN are similar in the Scott and Blackwood rivers. However concentrations of TP are much higher in waters flowing from the Scott and often exceed the guideline value of 0.03 mg/L.

River water is usually rich in oxygen and nutrients such as the oxidised forms of nitrogen (nitrate NO_3^- or nitrite NO_2^-) that generally peak with high flows (usually in July–September). In contrast when oxygen is low near the sediment, concentrations of nitrogen as ammonium (NH_4^+), and phosphate as inorganic phosphate (orthophosphate or Filterable Reactive Phosphate FRP) may be higher. However release of phosphorus from the sediment is complex and not always evident during the prolonged periods of low oxygen conditions as it may bind to iron in the sediment.

To understand where the nutrients are coming from and the effect they may be having on algal blooms and plant growth, we need to examine water quality at the individual sampling locations from the riverine areas, Blackwood (BRF01 and 02) and Scott (SRF1), through to the marine areas near the mouth (HF01) (Figure 3.14a). Although concentrations of total nitrogen (TN) and phosphorus (TP) vary greatly, the highest concentrations clearly correspond to periods of increased flow predominantly in winter. TN concentrations generally exceed guideline values (0.75 mgL^{-1}) as shown by the darker bars. Nitrogen concentrations are much lower and within acceptable limits when flow is reduced. Highest concentrations were recorded at Scott River and in the Molloy Island area, and decreased downstream except for the anomalous wide range at HF01 (the most marine area). This decrease closer to the estuary mouth was probably due to dilution of estuarine water with inflowing marine water.

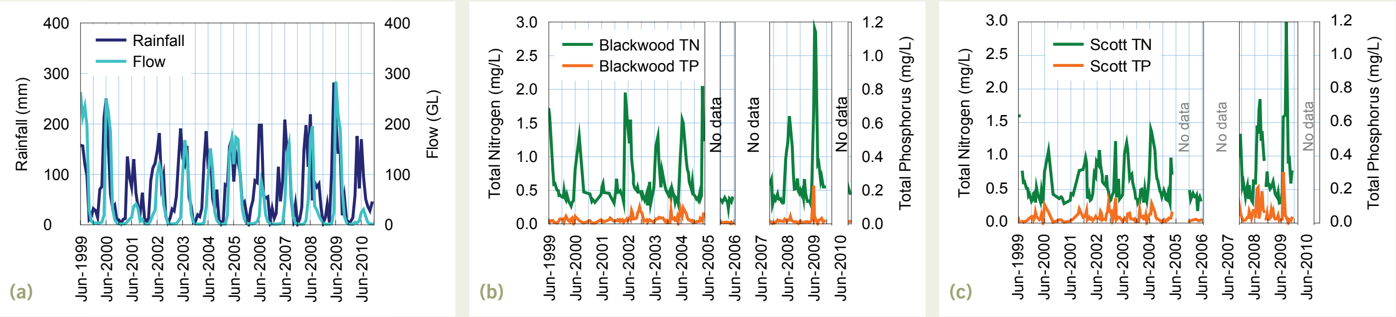


Figure 3.13 Rainfall (mm), river flow (GL) and surface water concentrations of total nitrogen and total phosphorus (mg/L) in June to December 1999–2010 in the estuarine waters of the Blackwood and Scott Rivers. ANZECC/ARMCANZ guideline values for TN 0.75 mg/L and TP 0.03 mg/L. Courtesy V. Forbes DoW 2011

Total phosphorus concentrations (Fig 3.14b) are also highest during periods of high flow, and are above the guideline value of 0.03 mgL^{-1} in the Scott and around Molloy Island. This points to the Scott River as a source of nutrient pollution and the commonly experienced algal problems around Molloy Island which are a response to availability of nutrients.

Although river flows in winter bring the largest loads of nutrients to the estuary, lower nutrient concentrations in the estuary when river flow is low in summer can be deceptive, and not necessarily indicative of improvements in water quality. Summer is ideal for algal and plant growth, when nutrients brought to the estuary are incorporated into organic matter. Abundant aquatic vegetation can be viewed as a temporary nutrient store or 'sink', which in turn decomposes adding to the sediment nutrient stores that can be recycled back into the water.

Rainfall and streamflow in summer can also bring additional nutrients, increasing the likelihood of blooms, particularly the types that favour lower salinity. The issue of summer and autumn blooms is an increasingly widespread problem in South West estuaries with the most spectacular event being the toxic blue-green *Microcystis* bloom in the Swan–Canning in 2000. See (*SWANLAND* Box 3.4 pg 102–103 *Tiny cells on the rampage take a city's playground off limits*). With projections of increased summer/autumn rainfall with a changing climate, more frequent and intense nuisance algal blooms are increasingly likely in the Hardy, as they are in all our other estuaries.

The focus of this chapter was the estuary's response to features and activities in the catchment that have affected water flow, tidal flows, sedimentation, and nutrients in the system. In the case of the Blackwood, nitrogen loads are particularly high while phosphorus is predominantly derived from the intense agriculture in the Scott. These nutrients are particularly concentrated at the confluence of the rivers around Molloy Island where they accumulate in the sediment as water slows. Furthermore, in this area where saline and fresh water mix, the stratified conditions with low oxygen at the sediment surface facilitates the release of stored nutrients that support additional algal growth. This is one aspect of the biological response to the catchment described in Chapter 4.

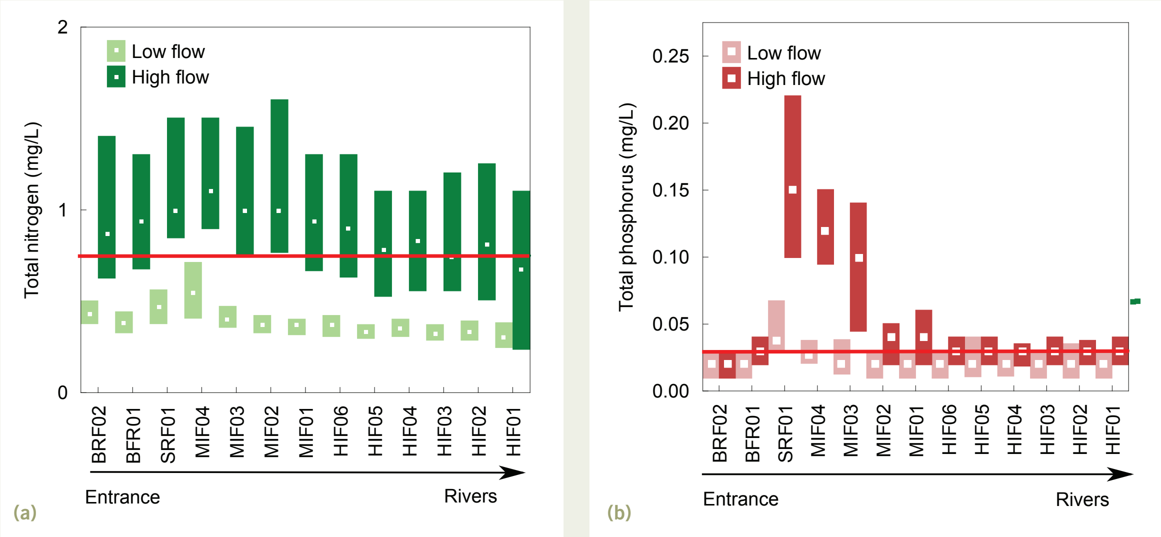


Figure 3.14 Total **(a)** nitrogen and **(b)** phosphorus in water samples collected at locations throughout the Blackwood BR, Scott River (SR) and Hardy Inlet (MF Molloy Is area and HIF Delta and Inlet channel). 1999–2010. High flow — winter (June to September) and low — summer flow (November to February). Median values white squares with 20th to 80th percentile range. Red line ANZECC/ ARMCANZ guideline valuese. Courtesy V. Forbes DoW 2011.

Pied Oystercatchers feeding among rocks exposed by dredging the channel January 2012. A. Brearley.

Chapter 4

THE ESTUARY — BIOLOGICAL ASPECTS

Chapter 4

The estuary – biological aspects

'The finely woven pattern of life in fresh waters and estuaries is most difficult to unravel, and subtle changes in floral and faunal population composition, hardly noticeable at first, may eventually have far reaching results on the whole pattern. Often long-term observations are necessary before man-made effects can be distinguished from the natural changes that may occur.' Sir Frederick Russell Introductory remarks at the Royal Society (London) discussion on *Freshwater and estuarine studies of the effects of industry* (1972). Quotation used by Hodgkin (1978) as the introduction the stability of the system in the ecological assessment of the Blackwood River Estuary.

Estuarine conditions are naturally variable. They undergo huge changes in all parameters: from fresh to hypersaline, from clear to turbid, from cold to warm waters. Changing nutrients add another layer of complexity on relatively short time scales. Therefore, estuarine biota are generally limited to a few types which are tolerant of changes, or those that can recolonise from nearby fresher or marine habitats when conditions are appropriate.

In this chapter we examine the changes in the biota of the Blackwood Hardy system since the 1974–1975 studies in the context of our long-term understanding of the estuary.

Salt tolerant paperbarks *Melaleuca cuticularis*, lining the banks of a quiet cove April 2008. A. Brearley.

4.1 Habitats and populations

In the 1970s, five habitats were differentiated to focus investigations of the algae, aquatic plants, invertebrates, fish and birds using the estuary:

(i) The **water body**, regarded as the most dynamic part of the system in response to freshwater flows from the rivers and seawater incursions brought by tides, influencing salinity, temperature, turbidity and light.

(ii) The **sediments** varying across the estuary in texture from coarse well-sorted sand to fine sand and clays with organic material, and vertically from the surface of clean pale well-oxygenated to deeper black anoxic conditions producing hydrogen sulfide. Sediments were sometimes covered by a film of fine organic matter resuspended by water movement.

(iii) **Submerged aquatic plants** principally *Ruppia* and small algal epiphytes.

(iv) **Hard substrates** of rock, logs and artificial structures, such as wooden jetties.

(v) **Marginal swamps** of rushes submerged regularly by tidal changes and other areas inundated less often during floods.

Hodgkin also commented that the estuary was not a closed system and both the river and the sea brought nutrients and flora and fauna into the system. The aquatic fauna was grouped into categories according to time spent in the estuary and breeding. The 'true-estuarine' animals with self-maintaining populations within the estuary are those able to contend with the extremes of salinity and favouring shallow, calm waters.

4.2 Algae and aquatic plants

Photosynthetic algae and aquatic plants in the estuary vary greatly in size, from tiny single cells (unicellular phytoplankton) in the water column which may aggregate into slicks or blooms through to the larger free-floating and attached macroalgae, and the seagrasses *Ruppia*, *Halophila*, and *Zostera*. These seagrasses are fine and quick growing types, not the large or robust longer-lived, slower-growing species found in the ocean and the most open estuaries of Oyster and Princess Royal Harbour at Albany (see sections 3.5 Sediment nutrient stores and 3.6 Sediment nutrient fluxes). To account for these differences in seagrass form, and avoid comparison with marine systems, the term submerged aquatic vegetation or SAV is sometimes used to describe a number of aquatic plants including estuarine seagrasses. SAV are considered important in many places because they provide important habitat for other biota, greatly influence environmental conditions in the water body, but are themselves affected by deteriorating water quality.

The productivity of vegetation in the fringing 'marginal swamps' and waters of the Blackwood-Hardy, and contributions of biomass and nutrients to the sediments and water were extensively studied by Congdon and McComb (1979, 1980 and 1981) forming a basis for understanding how other estuarine systems in the South West function. However, although studies of the vegetation in other estuaries in the South West followed, the Blackwood system was not examined again until 2000 when the DoW initiated studies of the composition and distribution of the aquatic flora, along with sediment quality and nutrient stores and additional surveys of macroalgal and Ruppia in 2008 by the Marine and Freshwater Laboratory art Murdoch University (Hale *et al*. 2000; Wilson and Paling 2008). Forty years later our focus on the aquatic plants is linked with concerns that the abundance of algal blooms, overgrowth of large algae and sporadic appearance of undesirable species, including blue-green algae and dinoflagellates are indicative of higher nutrients and deteriorating water quality (Hale *et al.* 2000; Wilson and Paling 2008). Less research has been conducted on other biota.

Phytoplankton

Phytoplankton blooms and small summer of outbreaks of green algae in the Blackwood-Hardy were not regarded with concern in 1976, although problems were evident in other systems. When water quality monitoring by the Water and Rivers Commission commenced in 1998, the types of phytoplankton were generally characteristic of a healthy system dominated by diatoms and cryptophytes in summer and chlorophytes in winter, with infrequent and relatively small outbreaks of cyanobacteria (blue-green algae) and periods when phytoplankton numbers were high in West Bay (Hardcastle and Cousins 2001).

The growth of phytoplankton is generally limited by the availability of dissolved inorganic nitrogen (DIN). Cyanobacteria, which can utilise or 'fix' nitrogen from the atmosphere, can grow when DIN is depleted and concentrations of phosphorus are high. This can give them a competitive advantage over other types of algae. Thus the types of algae also indicate changes in the usual balance of nutrients.

The 12 years of almost continual bi-weekly monitoring enables us to look for consistent patterns or deviations in water flow, nutrients, and expressions of these changes in terms of algal blooms in the water column (Figures 3.13 and 3.14). Concentration of soluble nitrogen suitable for algal growth varies over time in response to flow from the catchments. Generally the phytoplankton peaks follow the nutrient peaks. Nutrients released from the sediments (see sections 3.5 Sediment nutrient stores and 3.6 Sediment nutrient fluxes) may also contribute to microalgal growth particularly of motile dinoflagellates that can access the bottom waters. Fluctuations in a phytoplankton community can also be influenced by sunlight, temperature or grazing by invertebrates.

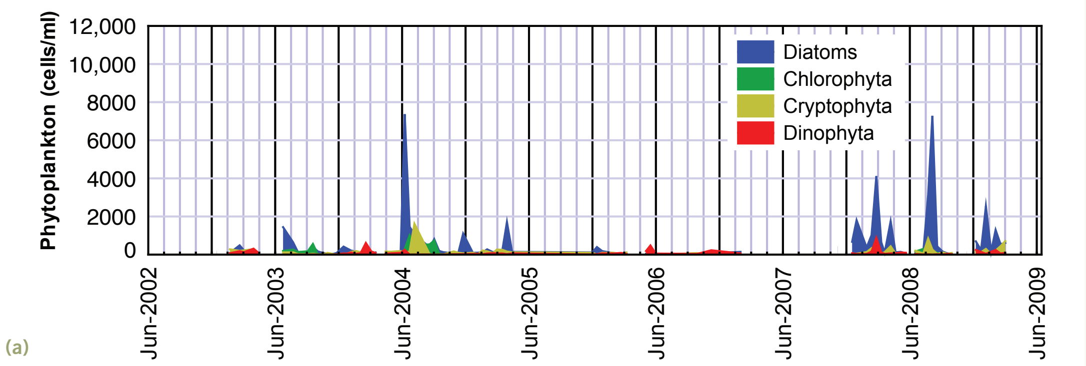
The types of phytoplankton quite clearly change over time. Also parts of the Blackwood-Hardy, such as the seawater area near the mouth and upstream, respond differently (Figure 4.1). Phytoplankton species may also reflect environmental factors such as temperature, particular nutrients, light and salinity. Diatoms reflect the availability of silica.

Since June 2002, there appears to have been a shift from diatoms to another type of phytoplankton, the Cryptophytes. Similar shifts in phytoplankton communities in other parts of the world have been attributed to high rainfall years favouring diatoms and drier years favouring cryptophytes. This could be a response to availability of silica.

Diatoms, mostly the marine species *Skeletonema* cf *potamo* and *Chaetoceros* dominated the phytoplankton in 1999, 2001 and 2002. Generally diatoms are more desirable members of the phytoplankton as they provide food for filter-feeding organisms such as mussels and juvenile fish.

The dinoflagellate (Dinophyta) *Prorocentrum cordatum*, present throughout the sampling, was particularly abundant in June and July 2001. Blooms appeared to correspond with periods when the estuary was stratified, oxygen was low and nutrients were released from the sediment. Dinoflagellates, with a whip-like flagella, are motile and are thought to gain a competitive advantage over other free-floating algal cells. They can access nutrients throughout the whole water column, swimming between the surface during the day when light is abundant, and dropping to the bottom at night where nutrients are high. This behaviour allows them to multiply rapidly, and has gained them the nickname of 'estuarine cockroaches'. The higher abundance of dinoflagellates in areas upstream, around Molloy Island and in the riverine reaches corresponds with the area of stratification, driven by the salt wedge and organic matter from the catchment, and the ability of these algae to utilise the nutrients fluxing from the sediments.

A number of potentially harmful dinoflagellate species are now recorded from the inlet including *Dinophysis acuminata* (December 2003), *Gymnodinium complex* and *Prorocentrum minimum/ Karlodinium*. The presence of *D. acuminata* is of particular concern as it can cause Diarrhetic Shellfish Poisoning (DSP). The presence of dinoflagellates can be a useful indicator of water conditions. An increase in frequency is linked to deteriorating water quality — a pattern that is becoming all too familiar all around the coast. As dinoflagellate toxins are extremely potent, the presence of even small numbers of these algae is worrying. Toxin-producing species are not yet abundant in the Hardy but their presence is an indication of what we may expect in the future if water quality continues to decline.



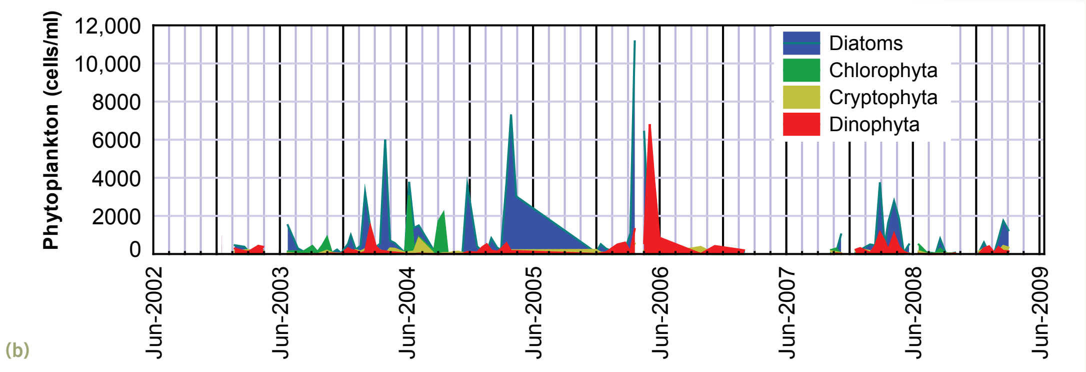


Figure 4.1 Phytoplankton groups sampled in the Hardy Inlet 2002- 2009. **(a)** Lower estuary basin and inlet channel, salinity>25 ppt. **(b)** Upper estuary including area around Molloy Island and tidal river, salinity 5-25 ppt. Courtesy V. Forbes DoW.

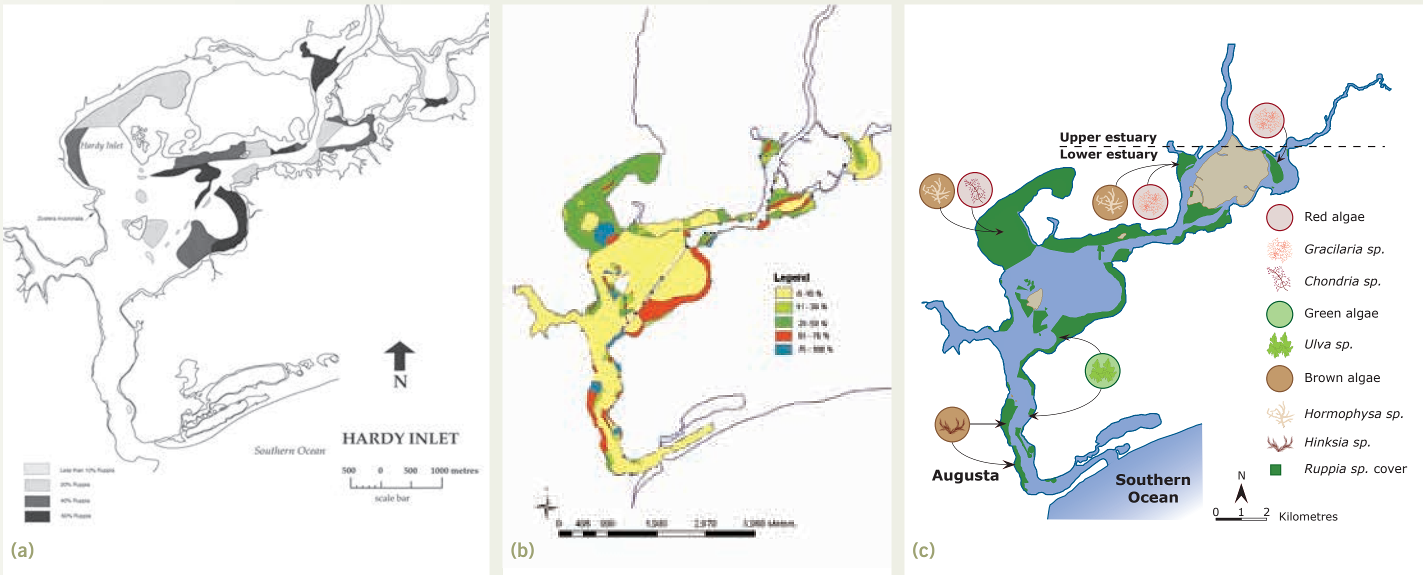
The cyanobacterium (blue-green alga) *Lyngbya aestuarii* has been recorded from the lower reaches of the Blackwood and Scott rivers and in the Upper Hardy Inlet and areas around Molloy Island since December 2006. *Lyngbya* usually appears as a black fuzzy filamentous or slimy scum on sediments and on plants. To date, blooms of *L. aestuarii* have not been toxic. However the presence of cyanobacteria which are able to tolerate low oxygen, with the ability to use atmospheric nitrogen, is a very real concern and indicates deteriorating conditions. *Lyngbya* blooms in other systems are known to respond to phosphorus, iron, tannins and decaying organic matter. The occurrence of these outbreaks in the Scott River and adjacent areas around Molloy Island may be linked to the high phosphorus concentrations in the waters. This is another warning sign of declining water quality and potentially affects swimming and boating in the estuary.

The cyanobacteria *Anabaenopsis* sp. and *Trichodesmium* have also been reported in the Hardy. Blooms of *Trichodesmium*, which is a marine open-ocean species, near the mouth are likely to be due to rafts of cells blown on shore and proliferating in the sheltered waters, rather than a direct response to estuary nutrients. However, the increase in these blooms, which can cause skin irritations, is a warning about the potential effects of algae that increase when additional nutrients pollute the water.

Microphytobenthos (MPBs)

Single or unicellular algae and bacteria not only live in the water column but also on the sediment or within the sediment (on and between particles). There is a variety of forms similar to groups found in phytoplankton that now appear to be more abundant, colouring the sediment or forming scums when nutrients are available. While little is known of the MPBs in the Hardy Inlet, recent research by Geoscience Australia in conjunction with the Department of Water has shown significant fluxes of nutrients from the sediments in some parts of the estuary. These nutrients may sustain MPBs, however the dynamics of the chemical and biological processes are not yet determined (Section 3.6 Sediment nutrient fluxes).

Blue-green algal Lyngbya bloom near Molloy Island December 2006. Courtesy A. Ramsay.



Map 4.1 **(a)** Distribution of *Ruppia* in the Hardy Inlet March 2000 (Hale *et al*. 2000). Intensity of shading indicate relative abundance 60–10% cover. **(b)** *Ruppia* in April 2008. **(c)** *Ruppia* (seagrass) and macroalgae distribution in 2008. Courtesy V. Forbes, DoW based on surveys of Wilson and Paling 2008. Note: *Ruppia* in all areas formed a dense canopy and shallow areas were covered with vegetation.

Aquatic vegetation — setting the scene 1970s

Aquatic vegetation in the 1970s was dominated by *Ruppia*, a seagrass species tolerant of varying salinity (See *SWANLAND* Box 8.3 page. 390 *This thing called* Ruppia). *Ruppia* grew in the marginal shallows of the tidal river in summer and year-round in the basin and inlet channel. It was most abundant in the stagnant waters of Swan Lake and the Deadwater. It did not grow in water less than 50 cm deep or deeper than 1.5 m, the depth limited by plant light requirements. Changes in biomass were attributed to senescence and water turbulence in summer, and grazing by swans. Another seagrass, *Zostera mucronata*, was confined to the lower estuary where salinity was generally higher, while the freshwater grass *Potamogeton pectinatus* was abundant around Molloy Island extending downstream into the basin in spring but disappearing as the waters became brackish (Bray 1978). A fourth species *Lepilaeana cylindrocarpa* was occasionally found in the basin area.

Following changes in the aquatic vegetation

Ruppia still dominated the aquatic vegetation in March 2000 (Hale *et al*. 2000) accounting for 90% of the plant biomass in the system (≈ 98.5 tonnes) (Map 4.1a). At Point Ellis in the lower inlet channel, particular note was made of the patchy *Ruppia* covered by epiphytic algal growth. In 2008, further investigations using slightly different techniques, indicated that *Ruppia* had increased markedly, particularly around the margins of the inlet channel, including Seine Bay, central basin, Molloy Island and North Bay. Abundance however decreased in the Deadwater as flow through the area increased with the eastwards migration of the channel. Although reasons for this overall increase are not known, experience in other estuaries such as Wilson Inlet indicates that *Ruppia* grows rapidly in sheltered estuaries where there are periodic flows of freshwater for germination and high nutrients to fuel growth. As nutrients are incorporated into biomass, they are no longer available for less desirable micro- and macro-algal growth, and *Ruppia* can be regarded as a store or sink for nutrients (Carruthers *et al*. 1998; Dudley *et al*. 2001).

The increase of *Ruppia* provides evidence that conditions have changed in the 25 years between surveys, and that meadows hold a large store of nutrients, as in Wilson Inlet. The presence and health of *Ruppia* in the Hardy Inlet therefore appears to be crucial. Loss of *Ruppia* without a substantial decrease in nutrients entering the system would result in a proliferation of undesirable algae.

The extent of *Zostera mucronata* also appears to have changed since the 1970s. In 2000 it was only observed in the basin area north-west of Point Trafalgar and Thomas Island, whereas in 1974 it was present in the lower inlet channel south of Point Ellis, in Seine Bay and in the Deadwater. The proliferation of epiphytes (small algae attached to other vegetation) in the Point Ellis area was suggested as a factor contributing to the loss or decrease in *Zostera*. By 2008, the species was not found at any of these locations. The increase of *Ruppia* and epiphytes however would have also made observations and identification difficult. Another small sea grass *Halophila decipiens*, documented by Kuo and Kirkman (1995), also appears to have disappeared. During the 1990s, this annual species formed large dense meadows along the sloping edge on the inlet channel. Equally interesting is the absence of records in the Hardy of *Halophila ovalis*, which grows in Flinders Bay and is recorded spasmodically in the marine reaches of estuaries throughout the South West.

Macroalgae clogging the water — smothering the bottom

In the 1960s (August 1966 and February 1967) unpublished records of Allender in Congdon and McComb (1976) noted only eighteen species of algae; nine green, four brown and five red species. They commented *'that brown algae were particularly sparse and that compared with other estuarine floras in south western Australia the flora is very depauperate*. This low diversity was attributed both *to the very short saline phase of the estuarine waters... and to the absence of rock and other solid substrates for attachment.'*

The same species were noted in 1974–1975, but were not considered abundant except for spring and summer blooms of the charophyte *Lamprothamnium papulosum* near Molloy Island and of the filamentous green alga *Rhizoclonium* in the Deadwater. Particular note was made of the 'nuisance' green algae *Cladophora* and *Chaetomorpha*, which although present were never abundant in the Blackwood but grew excessively in the Swan, Peel and Walpole.

Assessments of shifts in the types of algae since the 1970s are complicated by to name changes, queries about details of sampling stations and methodology. In the 1970s, macroalgae in the Hardy were regarded as neither diverse nor abundant when compared to other South West estuaries. Green algae such as *Cladophora*, *Chaetomorpha* and *Enteromorpha* were considered abundant only in the Deadwater. Sampling in March 2000 (Hale *et al*. 2000) and 2008 (Wilson and Paling 2008) indicated that algal abundance had increased and some species were more widespread (Map 4.2 a and b).

In 2000 larger algae were obvious in the southern, more-marine areas but not considered of 'nuisance' levels. Algal abundance was highest in the Deadwater area where sea lettuce *Ulva* (previously termed *Enteromorpha* sp.) covered about 40% of the area. However it was expected that the biomass of green algae could be much greater in spring (Map 4.2). High biomass of the epiphytic red alga *Polysiphonia* sp. was also recorded in the Deadwater. This shallow area, with large amounts of organic matter in the sediments and decaying wrack of seaweeds and remnants of marine life washed in with tides, provided ideal conditions for algal growth.

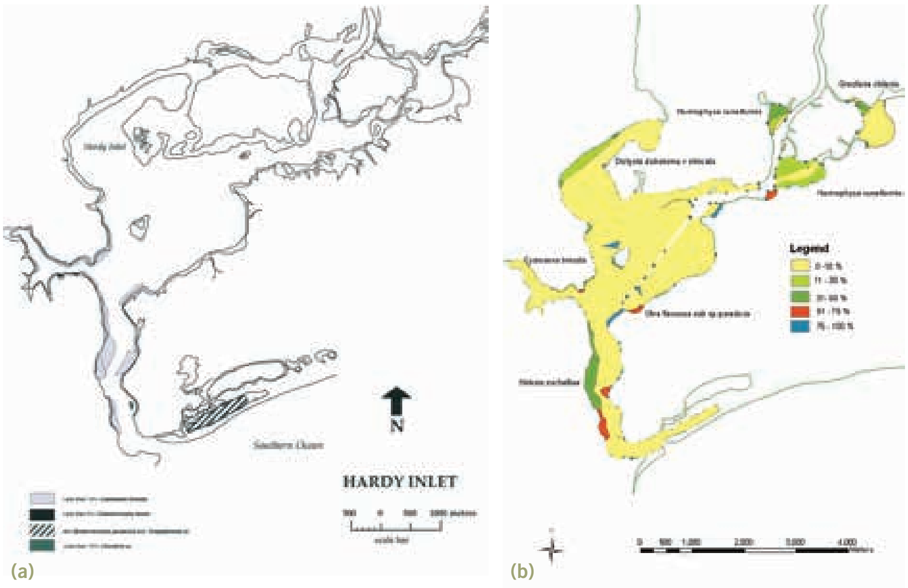
In 2000 there was an estimated 12.9 tonnes of macroalgae in the Hardy. Chlorophyta (green algae) accounted for 5.3 tonnes (41%) of the total biomass, Phaeophyta (brown algae) for 4.6 tonnes (36%) and Rhodophyta (red algae) 3.0 tonnes (23%). The principal Phaeophyte species were *Cystoseira trinodis* and *Dictyota furcellata*, Chlorophyte *Enteromorpha paradoxa*, and Rhodophytes *Polysiphonia* sp. and *Chondria* sp. Biomass was not estimated in 2008. In 2008, *Ulva* and small amounts of *Rhizoclonium* were recorded in the eastern side of the upper inlet channel and another small area near the mouth that was previously part the Deadwater. However, in 2008 most algae were no longer abundant in this area, now part of the inlet channel and subjected to relatively high water movement.

The large brown alga *Hormophysa cuneiformis* (previously *triquetra*) recorded near the mouth of the Scott in the 1970s was not recorded in 2000, but was found in 2008 to the west and south of Molloy Island. Another brown algae *Cystoseira trinodis* was recorded from the lower inlet and North Bay in the 1970s, and in 2000 was considered the dominant macroalga, growing attached to rocks along western edge of the inlet channel, central basin and around West Bay. In 2008 *C. trinodis* was found only on the northern side of the bay, although it was more widely distributed at Point Trafalgar, Thomas Bay, and on the eastern side of the main basin and channel, predominantly in rocky areas. In contrast *Dictyota*, a brown alga recorded in North Bay and around Molloy Island in the earlier studies of the 1970s, and in West Bay in 2000, now appears more abundant in sheltered areas and its identity confirmed as *D. cf dichotoma*.

Red algae have also changed over the years. *Hinksia* (previously *Giffordia*), an epiphytic species recorded in the 1970s, was not seen in 2000. It was however very common in 2008, particularly in the inlet channel and the more disturbed areas near the boat ramps and channel edges.

Similarly the red alga *Gracilaria chilensis*, now an obvious species in the Scott River-Molloy Island area, was not recorded here previously. However, this could be the unknown *Gracilaria* species recorded in the 1970s in the Deadwater and lower inlet.

There are other changes in the species records. *Lamprothamonion papulosum*, a species tolerant of saline conditions and common in the estuaries in the eastern part of Western Australia such as Wellstead, (See *SWANLAND* Pg 457, Fig 10.16), has not been documented in recent surveys of the Hardy. Similarly the freshwater *Potamogeton pectinatus* has not been observed. *Lepilaeana cylindocarpa* is another absence from recent surveys, perhaps not surprisingly as it is easily confused with the very similar *Ruppia*. In contrast the green alga *Polyphysa peniculus* (previously *Acetabularia*) was quite abundant amongst *Ruppia* in the estuary (Seine Bay) in 2008, although not mentioned in the 1976 reports. A voucher specimen collected by Hodgkin in Swan Lake was lodged in the WA Herbarium, indicating its presence at that time but reflecting the transient nature of some species indicative of changes in estuarine conditions (Figure 4.2).



Map 4.2 (a) Distribution and cover of dominant macroalgae March 2000 (Hale *et al*. 2000)
(b) Macroalgae percentage cover April 2008 (Wilson and Paling 2008).

Importantly, the monitoring programs provide robust documentation of conditions at a particular time, which allows us to know when subtle changes are occurring and if a system is deteriorating. The species changes between the surveys present a view of the system that, despite the transitory nature of some species, indicates an increase in marine species and overall abundance of macroalgae and algal epiphytes. This is indicative of more saline conditions and nutrient enrichment.

Almost 40 years after the 1970s studies in the Hardy, we appear to have an increase in species and an upstream expansion of more salt-tolerant or marine species. Large macroalgae and fine epiphytic algae, including some species known to grow rapidly when nutrients are present, have increased. These form large mats that accumulate in sheltered areas when water levels are low, or downwind where they decay and smell. Similarly the increase in *Ruppia* throughout the system provides additional evidence of nutrient enrichment. Despite its value as a habitat, it contributes to the wrack problem. It is perhaps illuminating to consider the locations where the macroalgae are most obvious, i.e. where water movement is reduced and in shallow water, namely where steams enter the large water body around Molloy Island, the Scott Basin and West Bay, and in the lower estuary near drains, from gardens, parks and roads in the Augusta townsite.

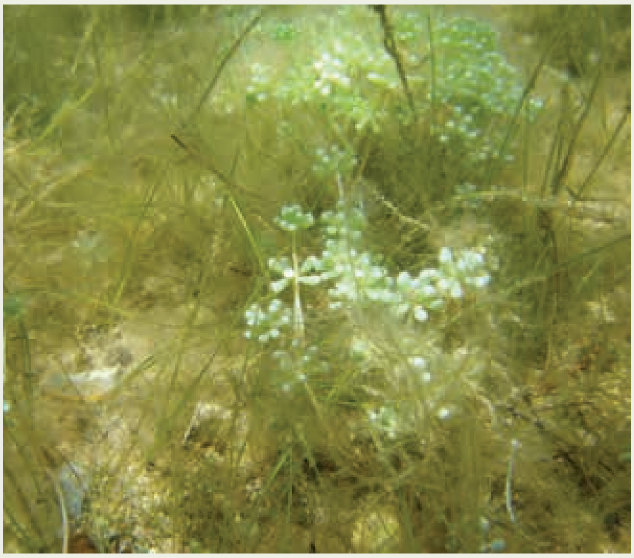


Figure 4.2 Aquatic vegetation in Seine Bay Hardy Inlet April 2008 showing the habitat used by small invertebrates and fish. The narrow green strands of *Ruppia* are covered with fine epiphytic algae, together with flower-like *Polyphysa peniculus*. A. Brearley.

4.3 Invertebrates

Studies of invertebrates conducted in the 1970s were primarily to assess the species present, how they responded to environmental conditions, the contribution to the diet of fish, and trophic flows within the system (Wallace 1976 a, b; Hodgkin 1978). Invertebrates were also one of the biotic and physical attributes used as indicators of estuarine health of seven estuaries on the west and south coast including the Hardy (Deeley 1999). They were more extensively surveyed by Brearley in 2008 at the time of nutrient assessments and flux experiments (Haese *et al*. 2010) and aquatic plant surveys (Wilson and Paling 2008).

The study in 1974–1975 identified 55 species of invertebrate, 40 of which were considered estuarine. Thirteen species dominated the fauna: three polychaete worms, four bivalve and three gastropod molluscs, two crustaceans and one insect. These constituted the main food resource for fish and birds. The study over summer and winter also allowed a seasonal assessment of changes in the fauna during the saline and freshwater phases. In general, the greatest number of species was found in samples collected at the marine end of the estuary. These were likely to have been recruited from populations outside the estuary when conditions were favourable, and numbers probably varied from year to year. In contrast, only a few species in the upper reaches.

Four ecological groupings were defined:

Group 1: Species confined to the tidal river and basin;

Group 2: Species found throughout the estuary;

Group 3: Species not found upstream of the lower basin (Stn 61 near Point Irwin); and

Group 4: Rush fauna.

It was noted that these groupings did not necessarily represent the species' physiological potential or distribution in other estuaries. Species in Group 3, although limited to the lower estuary in winter, did however extend upstream in summer as salinity increased. Species found throughout the estuary downstream of Station 150 in the Blackwood River (Group 2) were most abundant downstream of Molloy Island and less common in the tidal river reaches, particularly in winter (Table 4.1).

Animals confined to the upper reaches of the estuary (Group 1) include the tiny gastropod snail *Potamopyrgus*, the mussel *Xenostrobus securis*, and false mussel *Fluviolantus* (previously called *Anticorbula*). The bivalves were both known to tolerate low salinity; *Xenostrobus* closes the valves and becomes inactive in low salinity while *Fluviolantus* remains active at low salinity. However as they were also know to tolerate seawater. The absence of these bivalves from the marine part of the estuary was considered intriguing but attributable to the absence of firm substrate suitable for attachment, rather than a simple response to salinity. This absence of hard surfaces was also noted with respect to the low diversity of macroalgae in the Hardy when compared to other south west estuaries. Particular note was made of the aquatic vegetation, especially *Ruppia*, as a habitat for small molluscs and crustaceans and for juvenile fish. Among the largest of the crustaceans was the shrimp *Palaemonetes*, a species able to tolerate changes in salinity and able to breed within the estuary. *Palaemonetes* and the other invertebrates were found to be an important component in the diet of a number of fish species.

Benthic fauna 2008

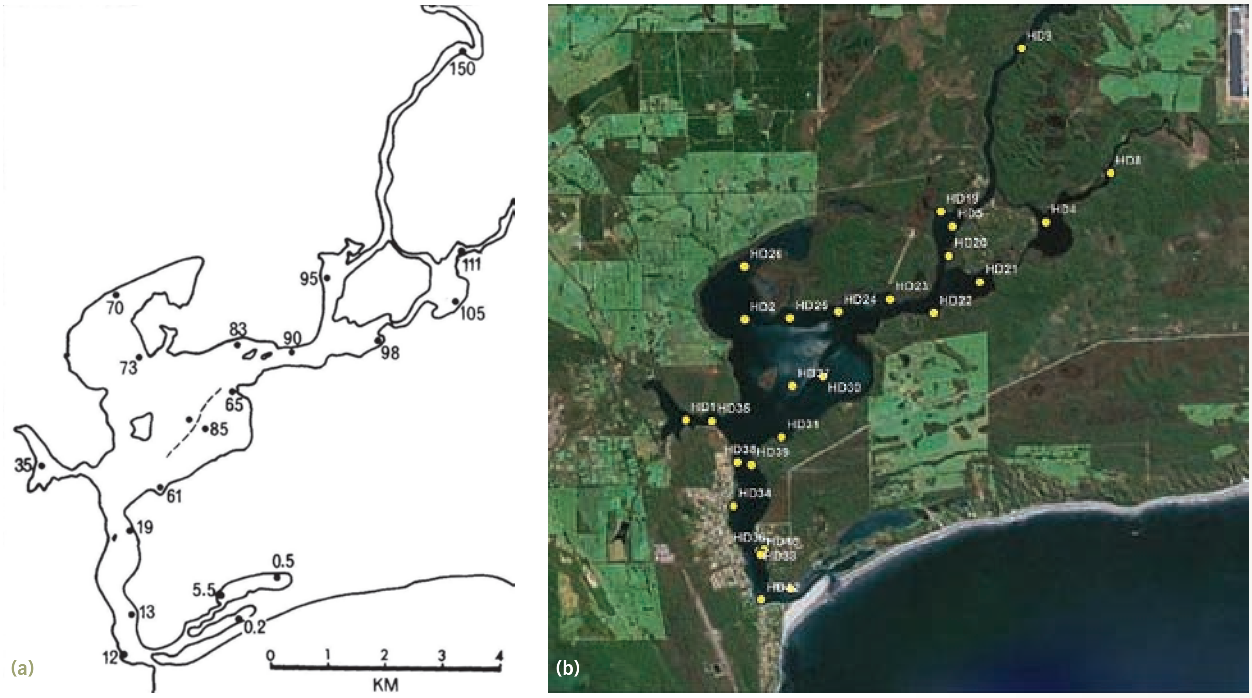
The survey in 2008 at 28 locations followed the sites investigated by Wallace in 1976 (Hodgkin 1978) and the surveys by the Department of Water and Geoscience Australia (Haese *et al*. 2010) (Map 4.3). Core samples were collected throughout the estuary and along the shoreline. The shore-based locations allowed more targeted sampling in areas of sand and in *Ruppia*. This allowed comparison of the types and abundance of fauna in the different habitats. In addition to the cores, larger fauna were sampled in 0.25 m^2 quadrats at Colour Patch and near the Yacht Club in West Bay. All animals to a depth of 30 cm and retained on a one centimetre mesh were counted on site.

The fauna collected in May 2008 was very similar to that recorded in 1974–1975. The same species were present and generally in the same areas. It was difficult, however, to determine change in the abundance of individual taxa as only summary records for 1974–1975 are available. In 2008, the small false mussel *Fluviolanatus amara* was still found only in the upper estuary. The tiny bivalve *Arthritica semen* was most common in the lower estuary where *Ruppia* was abundant. The identity and distribution of one of the largest bivalves, the sunset shell *Soletellina biradiata*, present in the 1970s is debatable (Willan 1993). Small elongate individuals were considered to be juveniles that colonised the main basin in summer. These now appear more likely to have been *Soletellina alba*, the dominant species in the estuary in 2008, found upstream as far as Molloy Island. *Soletellina* species are known to burrow in anoxic sediments, and may be able to cope in areas now subject to stratification. In contrast, the ribbed cockle *Katelysia* was not found at the sites surveyed in 2008. As it has short siphons, this is a species confined to the oxidised top five centimetres of sediment that could be affected by the now widespread stratification and low oxygen in the bottom waters. Additionally as *Katelysia* is more commonly found in areas of sand, the increase in *Ruppia* may have also reduced the area of preferred habitat. Changes in abundance of both *Katelysia* and *Soletellina* may not however be solely limited to environmental changes. For many years both bivalves were collected by fisherman for bait, so it is now difficult to know how abundant they were. It is widely acknowledged however that there were fewer *Katelysia* in the 1990s than in the quieter days of the 1970s, and the populations may have been depleted by these activities.

Two species of the scavenging gastropod, the dog whelks *Nassarius pauperatus* and *Nassarius burchardi*, were present in the 1970s. The most common species in the Hardy *N. pauperatus* is also found in other south coast estuaries. In contrast *N. burchardi* was the dominant species in estuaries along the west coast including the Swan. They were found in sandy areas and were most abundant near seagrass and most common in the lower estuary moving into the upper basin during the saline phase. Both species were present in 2008 but were not abundant. They were found only in the lower estuary, in cores collected in the Inlet Channel at East Augusta (2) and HDT3 (1), and in the larger quadrats (13) near in the Inlet Channel and Colour Patch (CP) in Seine Bay. This species commonly found in sand areas was most abundant in areas with *Ruppia*.

Laternula was also present in cores and quadrats in the lower estuary and around Molloy Island, indicating that it was well established in the Hardy. Although not recorded in the systematic quantitative coring of 1974–1975, it was seen at that time. Known from other estuaries where it burrows in fine sediments and amongst seagrass, *Laternula* appears to be tolerant of anoxic sediments.

The importance of habitat, principally *Ruppia*, for invertebrates and juvenile fish (which hide within it and feed on other small fauna), was clearly demonstrated by the sampling in vegetated and adjacent sand areas (Figure 4.4). *Ruppia* supported large populations of the



Map 4.3 Location collections **(a)** 1974–1975 and **(b)** 2008 (Background map Google Maps). In 1970s the ocean entrance was located adjacent to Dukes Head, with the lagoons of the Deadwater and Swan Lake lying behind the coastal dunes to the east. In 2008, growth of the sand bar from Dukes Head, deflected river flow through the Deadwater Channel and the ocean entrance relocated some 2 km eastwards leaving only a small Deadwater lagoon. From Hodgkin *et al*. 1978 and DoW.

Table 4.1 Principal benthic invertebrates and ecological groupings in the Hardy Inlet 1974–5 and 2008*.
Adapted from Wallace 1976 in Hodgkin 1978.

Ecological groupings 1978	Taxa group	Habitat	2008
Group 1 — Species confined to tidal river and basin			
Xenostrobus securis	Mollusca, Bivalvia	Hard substrates	√
Fluviolantus amara (*Anticorbula*)	Mollusca, Bivalvia	Soft sediments	√
Hydrobia buccinoides (*Potamopyrgus* sp. Estuarine)	Mollusca, Gastropoda	Ruppia and epiphytes	√
Group 2 — Species found throughout the estuary			
Capitella capitata	Polychaeta	Soft sediments	√
Scoloplos simplex	Polychaeta	Soft sediments	√
Simplesetia aequestis (*Ceratonereis erythraeensis*)	Polychaeta	Soft sediments	√
Arthritica helsmsii (*A. semen*)	Mollusca, Bivalvia		√
Melita zeylanica kauerti	Crustacea, Amphipoda	*Ruppia* and epiphytes	√
Corophium sp.	Crustacea, Amphipoda	*Ruppia* and epiphytes	√
Paracorophium sp.	Crustacea, Amphipoda	*Ruppia* and epiphytes	√
Palaemonetes australis	Crustacea, Palaemonidae	*Ruppia* and epiphytes	√
Pontomyia natans	Insecta, Chironomidae	*Ruppia* and epiphytes	√
Group 3 — Species not found upstream of lower basin (Stn. 61)			
Hydrococcus brazieri (*graniformis*)	Mollusca, Gastropoda	*Ruppia* and epiphytes	√
Tellina deltoidalis	Mollusca, Bivalvia	Soft sediments	√
Soletellina biradiata and *S. alba* (*Sanguinolaria*)**	Mollusca, Bivalvia	Soft sediments	√
Katelysia scalarina	Mollusca, Bivalvia	Soft sediments	Not seen
Group 4 — Rush fauna			**Not sampled**
Tatea preissi	Mollusca, Gastropoda	Mud surface	
Potamopyrgus sp.	Mollusca, Gastropoda	Mud surface	
Orchestia sp.	Crustacea, Amphipoda	Mud and algae	
Cyclograpsus audouinii	Crustacea Decapoda	Mud burrows and under logs	
Leptograpsus octodentatus	Crustacea Decapoda	Mud burrows and under logs	

* Current nomenclature 2008, in parentheses name used in 1978. *Ruppia* and epiphytes may include some larger algae. Rush fauna were not investigated in 2008.
** In common with other studies, it is now clear that two species of *Soletellina*, *S. biradiata* and *S. alba* were present in the 1970s, and S. alba was assumed to be juveniles.

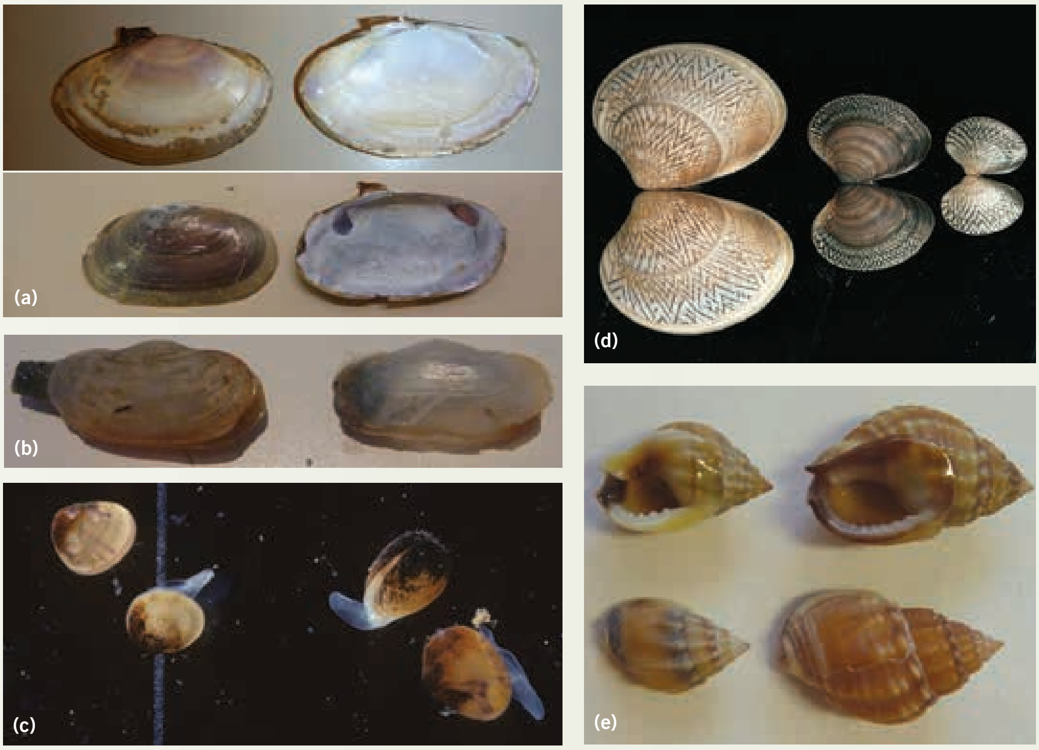


Figure 4.3 Common bivalves in Hardy Inlet. **(a)** *Soletellina biradiata* and *S. alba* (adult 50 and 45 mm). **(b)** *Laternula* (33–60 mm) note the slightly nacreous shell, fine sculpture of concentric lines crossed by fine striae, wide gape at posterior where the siphons emerge and the 'crack' characteristic of Laternulidae. **(c)** *Arthritica semen* (3 mm) is often abundant in eutrophic estuaries with abundant algae. **(d)** *Katelysia scalarina* (adult 45 mm) not found during surveys in 2008 was present in 1974–75 and commonly collected for bait. Although abundance of species in estuaries varies greatly, this species may no longer be present. **(e)** *Nassarius pauperatus* (15 mm) and *N. burchardi* (10 mm).

gastropod *Hydrococcus brazieri* that browses on epiphytic algae, amphipods *Corophium*, *Paracorophium* and *Melita* and the larvae of the midge *Pontomyia*. Hodgkin had noted that these species were particularly abundant in the *Ruppia*-dominated areas of the Deadwater. Currently, the fauna in the lower estuary around the urban areas of Augusta and Colour Patch in Seine Bay is more similar to that found in the Deadwater during the 1970s in terms of the growth of *Ruppia* and abundance of worms. Thus some of the attributes of the Deadwater as a habitat for invertebrates and possibly juvenile fish have not been lost from the system but relocated to the now more sheltered areas on the western margin of the estuary.

Few specimens of the shrimp *Palaemonetes* were collected in 2008, however sampling with cores was less likely to have collected these highly agile species.

Many small invertebrates burrow into the sediment where they play an important part in the physical breakdown of detrital plant material and their faecal pellets are an important part of the organic mud. During the course of a year, the volume of sediment that they ‘rework’ can be substantial and vary with the grain size and interstitial space of sediments. Burrowing can increase the depth of the oxidised surface layer (lightly coloured) relative to the deeper anoxic (dark coloured) layers and thus influences the release of stored nutrients. In turn, the depth of the surface oxygenated layer influences the fauna found in the sediment and their accessibility as prey for fish. The polychaete worm *Simplisetia* (previously known as *Ceratonereis*), generally living in surface sediment, was found in the stomach contents of fish in the 1970s. In contrast, the worms *Capitella* and *Scoloplos* that burrowed into the darkly-coloured anoxic sediments to a depth of 10 centimetres were considered to be less likely to be eaten. In 2008, *Simplisetia* and *Capitella* were the most common polychaetes. *Capitella*, a species usually associated with organic material and nutrient enrichment, were most abundant in cores collected from Colour Patch.

In the study of food used by fish in the Blackwood, Wallace (1976b) found that the abundance of worms as a dietary item were probably underestimated, as the soft bodies were difficult to recognise in stomach samples. In general invertebrates were the major food source for fish, which fed opportunistically on a wide variety of items and predominately on the most abundant species.

The importance of plant material to the fish diets is little known. Algae and *Ruppia* have been found in the stomachs of black bream, silver bream trevally and garfish. Only garfish, which ate *Ruppia*, were considered herbivorous, although black and silver bream were considered omnivorous and known to eat seagrass and large algae. However, there were questions as to how much of this material was digested. Similarly a number of fish consume detritus, but the only species known to use the microbiota as a source of food was the sea mullet. Fish including the resident black bream, hardyheads and gobies are known predators on invertebrates. Prey taken by black bream is perhaps the most varied. Bream characteristically are opportunists that feed on whatever food is available. Carnivorous fishes, such as tailor, mulloway and flounder, predominantly fed on the shrimp *Palaemonetes* and other small fish.

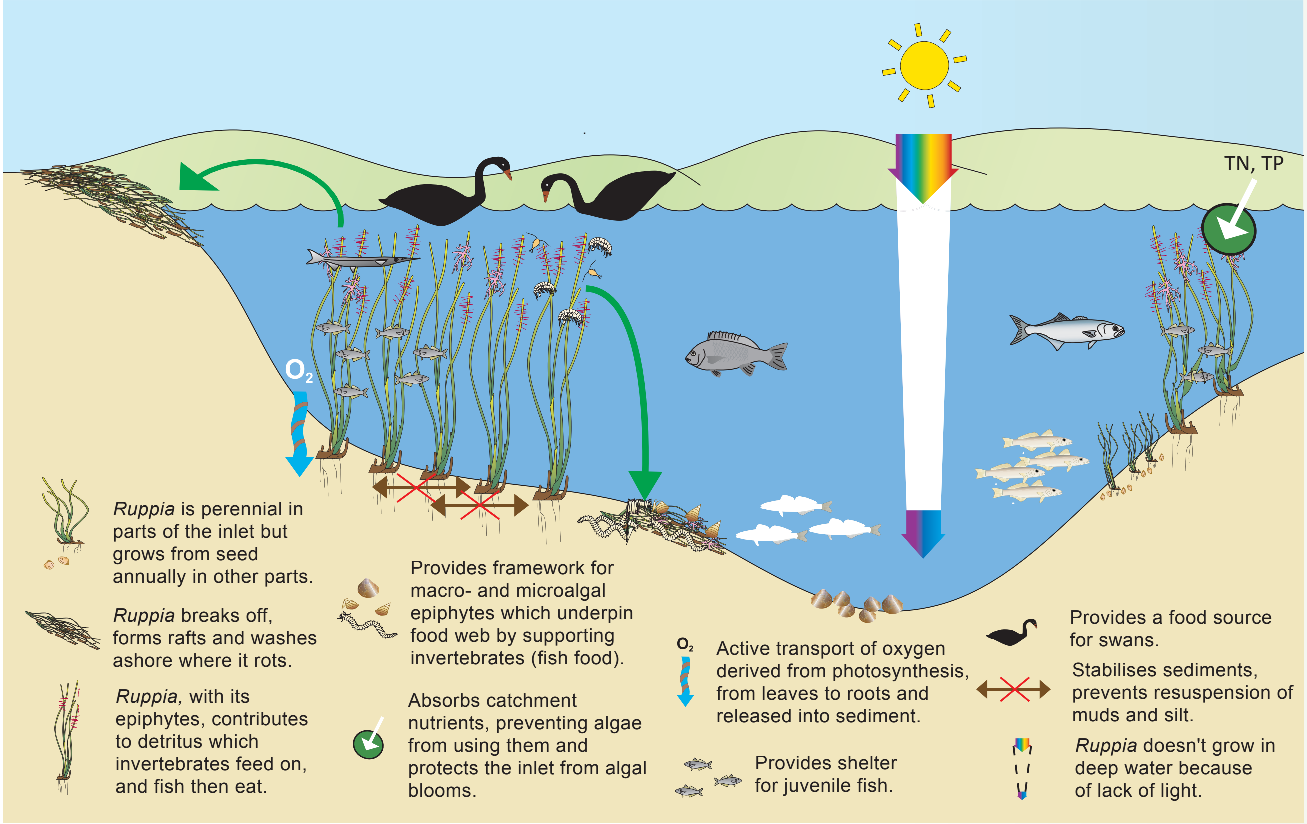


Figure 4.4 Ecology in the Hardy Inlet estuary of the Blackwood River. Illustrating interactions between aquatic vegetation (*Ruppia* and algae), invertebrates, fish and birds and the importance of *Ruppia* to the ecosystem. Courtesy V. Forbes DoW.

4.4 Fish and fisheries

The health and abundance of fish in an estuary is always of great interest to visitors and residents, primarily as a determinant of what they might catch, but also as an indicator of how the system is operating. Fish studies in the 1970s were central not only to understanding the biology of fishes and fishing activities in the Hardy estuary, but how fish use other estuaries and coastal regions of the south west (Caputi 1976; Lenanton 1976 1977). More recently another study in the Hardy and in Flinders Bay expanded on the earlier assessment of the estuary as a nursery area and assessed its response to seasonal environmental changes (Valesini *et al*. 1997). In 2005 the decline of fish stocks prompted a survey of recreational fishers and fish catches (Prior and Beckley 2007; Beckley and Ayvazian 2007). Concerns about the health of the black bream, particularly survival of larvae and juveniles and recruitment into the population, have also been the impetus for assessing stock (Department of Fisheries 2004), biology and restocking potential (Jenkins *et al*. 2006), and several workshops (Western Australian Fish Foundation 2007).

In 1974–1975, the system was regarded as being as rich as other south coast estuaries, with 57 fish species recorded. It is worth noting that the comprehensive studies along the coast and in the Blackwood, initiated by Dr Rod Lenanton and Dr Nick Caputi (now at the Department of Fisheries) and further developed by Emeritus Professor Ian Potter of Murdoch University, Dr Glenn Hyndes (currently Edith Cowan University), Dr Neil Loneragan, and colleagues, formed the basis for understanding the diversity and habits of fish populations in the South West.

As in the other estuaries of Swanland, the fishes can be grouped according to how they use the estuary:

Marine stragglers: Enter an estuary infrequently when conditions are favourable and breed in the ocean.

Marine-estuarine opportunists: Breed in the ocean and juveniles enter to feed and grow in the sheltered productive waters of either the estuary or coastal marine habitats.

Estuarine/marine: Breed in either an estuary or in sheltered coastal areas.

Solely estuarine: Complete their life cycle in an estuary.

Semi-anadromous: Live in the ocean but spawn in the upper estuary and juveniles develop in the estuary and return to the ocean as maturing adults.

Anadromous: Live and feed in the ocean and pass through an estuary on their way to distant inland freshwater areas to breed, with the maturing juveniles returning to the ocean.

Freshwater: Live in the river reaches and may be flushed into estuarine areas during periods of high river flow.

Consideration of the different groupings indicates that the species and their abundance in a estuary depends on a number of factors:

- immediate offshore habitats that influence the type of fish in the area;
- availability of breeding stock along the coast, controlled to some extent by larger scale oceanic effects;
- marine connection through the sand bar; and
- conditions in an estuary in terms of salinity and other environmental conditions, such as oxygen and suitable food and shelter.

ABOVE: Blue spotted flathead (*Platycephalus speculator*) and BELOW: estuary catfish (*Cnidoglanis macrocephalus*) both species feed on invertebrates burrowing in the sediment. Courtesy S. Morrison.

(See *SWANLAND* Overview: Fish and Fisheries pages 59–65, also Chapters and Boxes 2.11–2.16, 5.6, 7.1, 8.4 and 8.5 and 10.2 for particular species biology).

Fish living in or visiting the Hardy

The patterns reported in the 1970s (Lenanton 1977 1982 and 1984) were supported by studies in 1994 (Valesini *et al*. 1997) (Table 4.2). In the 1970s estuarine black bream *Acanthopagrus butcheri* were most abundant in the upper reaches of the estuary (tidal river and Molloy basin) in summer, moving downstream to the lower estuary during high winter flows, although some were present year round in Swan Lake and the Deadwater. With regards to the status of fish populations in 2010, we need to consider changes in the ocean entrance through the development of the sandbar to the east and the present flow of water through the coastal lagoon (the 'Deadwater'), a major fish habitat which was documented in the 1970s and 1990s.

In both study periods large numbers of juveniles of Marine-Estuarine Opportunists such as striped trumpeter *Pelates sexlineatus*, silver bream (tarwhine) *Rhabdosargus sarba*, yellow-eye mullet *Aldrichetta forsteri*, sea mullet *Mugil cephalus*, and King George whiting *Sillaginodes punctata* were more common in the estuary than in Flinders Bay, preferentially using the estuary as a nursery area. This is a feature common in other large estuaries on the lower west coast (Swan and Peel-Harvey).

In contrast, juveniles of another opportunist, the yellowfin whiting *Sillago schomburgkii*, were moderately abundant in both environments. The blue sprat *Spratelloides robustus* and southern school whiting *Sillago bassensis* were more abundant in Flinders Bay than in the estuary, as is also the case in other estuaries and nearby marine embayments in the south west. However, certain marine species e.g. sea trumpeter *Pelsartia humeralis* and the stargazer *Lesueurina platycephalus*, which were relatively common in Flinders

Table 4.2 Fish grouped according to habitat and breeding areas in areas of the Hardy Inlet 1994. Forty nine species collected by seine netting during the day and night every six weeks February to December 1994.
Adapted from Valesini *et al*. 1997. Categories as defined by Potter and Hyndes 1999.

	Whole estuary (%)	Estuary basin (%)	Entrance channel (%)	Deadwater lagoon (%)	Flinders Bay (%)
Species					
Solely marine	0	0	0	0	0
Marine straggler	40.5	32.3	38.2	13.1	19.2
Marine-estuarine opportunist	28.6	29.0	29.4	47.8	23.1
Estuarine/marine	21.4	25.8	20.6	21.7	38.5
Estuarine	9.5	12.9	11.8	17.4	19.2
Total number species	**42**	**31**	**34**	**23**	**26**
Individuals					
Solely marine	0	0	0	0	0
Marine straggler	0.3	0.5	0.6	0.1	8.1
Marine-estuarine opportunist	17.2	17.9	28.3	0.5	7.3
Estuarine/marine	43.1	35.4	57.3	36.8	3.8
Estuarine	39.4	46.2	13.8	53.7	80.8
Total number individuals	**51,706**	**10,031**	**16,654**	**25,021**	**3,110**

Bay and along the coast, were not collected in the Blackwood or other nearby estuaries. This illustrates that the use of estuaries as a nursery depends on the particular species and presumably opportunities in either area. The far higher abundance of fishes in the Blackwood estuary than in Flinders Bay suggests that the estuary provides a greater source of food and/or protection than the nearby moderately protected and nearshore marine waters, a situation probably typical of the coastline of southern Australia (Lenanton 1982).

Overall, the estuary basin and entrance channel areas were dominated by the small hardyheads or atherinids *Leptatherina wallacei*, and *L. presbyteroides*, and the long-finned goby *Favonigobius lateralis*, which are among the most abundant fish in estuaries throughout temperate Australia. Although small and perhaps not of great interest to people looking for fish for dinner, these are important consumers of algae and are prey for the carnivorous fish much-favoured by fishers.

In the studies of the 1970s and 1994, the high abundance of fish (particularly juveniles in the Deadwater) was generally attributed to the growth of *Ruppia*, which provides shelter and food for fish, and more importantly for small invertebrates, the major food resources for large and small fish. The 1994 study also highlighted the lower diversity of fish species in the Deadwater suggesting that this reflected the limited access from the estuary through the narrow connecting shallow channel. However those species that did enter — the marine estuarine-opportunists (tarwhine, yellow-eye mullet, King George whiting, sea mullet, and the small hardyheads) — reached higher densities in the Deadwater than in the inlet channel and basin, presumably to capitalise on the productive protected environment and more stable salinity during winter when marine species leave the estuary. These findings supported the idea of the special status of the Deadwater, the loss of which (with the migration of mouth to the east) is seen as detrimental to successful fishing in the Hardy. It is interesting to note however that the *Ruppia*-dominated habitat in the equally shallow sandy area of Seine Bay bordered by the Caravan Park is not seen in the same light and regarded as a nuisance, contributing to accumulations of decaying organic matter.

Fishing industry — commercial and recreational

Commercial fishing

The commercial catch in the Hardy Inlet is principally based on yellowfin whiting, sea mullet, yellow-eye mullet, and Australian herring. Recently the catch has been dominated by whiting (mostly yellowfin), but in years of low whiting catch, catches of yellow eye-mullet are higher (Figure 4.5). Black bream constitute a relatively small component of the commercial catch, with most taken in winter. Between 1998 and 2002 the total commercial black bream catch was about 4374 kg (4.3 tonnes), averaging less than one tonne per year. The largest catch was in 1983 and comprised 3.6 tonnes (DoF 2004). The apparent increase in the percentage of black bream in the 2010 catch is somewhat misleading, and a reflection of the decrease in the whiting caught. The average annual commercial catch of bream since 1978 is 1.2 tonnes, which has been maintained over the last ten years (2001–2010). In the last 30 years the number of fishing units that supply fish to markets and regional restaurants has decreased from six licences in 1979–1987, to five in 1998 to one license in 2000.

Recreational fishing

Recreational fishing has been a popular activity for a long time. A survey in 1974–1975 documented the recreational catch as black bream (20 tonnes), yellowfin whiting (12.8 tonnes), Australian herring (9.2 tonnes), King George whiting (2.5 tonnes), silver bream (2.3 tonnes), tailor (2.2 tonnes) and skipjack trevally (2.2 tonnes) (Lenanton and Caputi 1976, Caputi 1976). The total of 51.2 tonnes was estimated to represent 3.8 fish per angler per hour.

Since that time recreational fishing pressure has increased substantially and catch rates have declined. Reasons for the decline popularly focus on commercial activities. A survey of shore and boat-based fishing (interviewing 1212 angler groups), conducted over 144 days between September 2005 and August 2006, found that yellowfin whiting (47%) and Australian herring (17%) dominated the catch, although black bream (6%) was the most commonly targeted

Table 4.3 Fish species in Blackwood-Hardy estuary system 1994. Listed in order of decreasing abundance (%) in the estuary basin in comparison to other habitats of the entrance channel, Deadwater lagoon and Flinders Bay. Summarised and adapted from Valesini *et al*. 1997.

Common name	Species name	Category	Estuary basin (%)	Entrance channel (%)	Deadwater lagoon (%)	Flinders Bay (%)
Wallace's hardyhead	*Leptatherina wallacei*	E	35	8	24	
Long-finned goby	*Favonigobius lateralis*	E&M	21	17	12	
Presbyter's hardyhead	*Leptatherina presbyteroides*	E&M	14	40	25	76
Six-lined trumpeter	*Pelates sexlineatus*	O	12	21	1	
Long-headed goby	*Afurcagobius suppositus*	E	6	1	<1	
Tarwhine	*Rhabdosargus sarba*	O	4	5	5	<1
Elongate hardyhead	*Atherinosoma elongata*	E	3	3	28	
Blue spotted goby	*Pseudogobius olorum*	E	2	1	1	
Yellow-eye mullet	*Aldrichetta forsteri*	O	2	2	2	1
Southern anchovy	*Engraulis australis*	E&M	<1	<1		
Yellowfin whiting	*Sillago schomburgkii*	O	<1	<1	<1	2
Small-toothed flounder	*Pseudorhombus jenynsii*	O	<1	<1	<1	<1
Bridled goby	*Amoya bifrenatus*	E&M	<1	<1	<1	<1
Blue weed whiting	*Haletta semifasciata*	S	<1	<1		
Old wife	*Enoplosus armatus*	S	<1	<1		
King George whiting	*Sillaginodes punctata*	O	<1	<1	1	
Blue sprat	*Spratelloides robustus*	S	<1	<1	<1	2
Sea mullet	*Mugil cephalus*	O	<1	<1	1	<1
Banded (common) toadfish	*Torquigener pleurogramma*	O	<1	<1	<1	<1
Rough leatherjacket	*Scobinichthys granulatus*	S	<1	<1		<1
Brown-spotted wrasse	*Pseudolabrus parilus*	S	<1	<1	<1	
Cobber/estuarine catfish	*Cnidoglanis macrocephalus*	E&M	<1	<1	<1	4
Toothbrush leatherjacket	*Penicipelta vittiger*	S	<1			
Hairy pipefish	*Urocampus carinirostris*	E&M	<1		<1	<1
Southern sea garfish	*Hyporhamphus melanochir*	E&M	<1			<1
Blue spotted flathead	*Platycephalus speculator*	E&M	<1	<1		<1
Crested weedfish	*Cristiceps australis*	S	<1	<1		<1
Southern school whiting	*Sillago bassensis*	S	<1	<1		5
Trumpeter whiting	*Sillago burrus*	O	<1			
Brownfields wrasse	*Halichoeres brownfieldii*	S	<1			
Rock flathead	*Platycephalus laevigatus*	S	<1			
Australian herring	*Arripis georgianus*	O		<1	<1	<1
Western Australian salmon	*Arripis truttaceus*	O			<1	
Prickly pufferfish	*Contusus brevicaudatus*	O		<1	<1	<1
Ocellated pipefish	*Stigamatophora argus*	S			<1	<1
Goatfish	*Upeneichthys sp.*	S		<1		
Skipjack trevally	*Pseudocaranx dentex*	S		<1		
Elongate flounder	*Ammotretis elongata*	S		<1		<1
Gobbleguts	*Apogon rueppellii*	E&M		<1		
West. Aust. Pink snapper	*Pagrus auratus*	S		<1		
Silver drummer (buffalo bream)	*Kyphosus sydneyanus*	S		<1		
Yellowtail	*Trachurus mccullochi*	S		<1		
Sea trumpeter	*Pelsartia humeralis*	SM				4
Flathead pygmy-stargazer	*Lesueurina platycephala*	SM				3
Lemon tongue sole	*Paraplagusia unicolour*	SM				1
Common hardyhead	*Atherinomorus ogilbyi*	O				<1
Southern fiddler ray	*Trygonorhina fasciata*	SM				<1
Beaked salmon	*Gonorynchus greyi*	O				<1
Sweep	*Scorpis georgianus*	SM				<1
Species total number			**31**	**34**	**23**	**26**
Fishes total number			**10,031**	**16,654**	**25,021**	**3,110**

KEY: E – estuarine, E&M – estuarine/marine, O – opportunist, S – marine straggler, SM – solely marine.

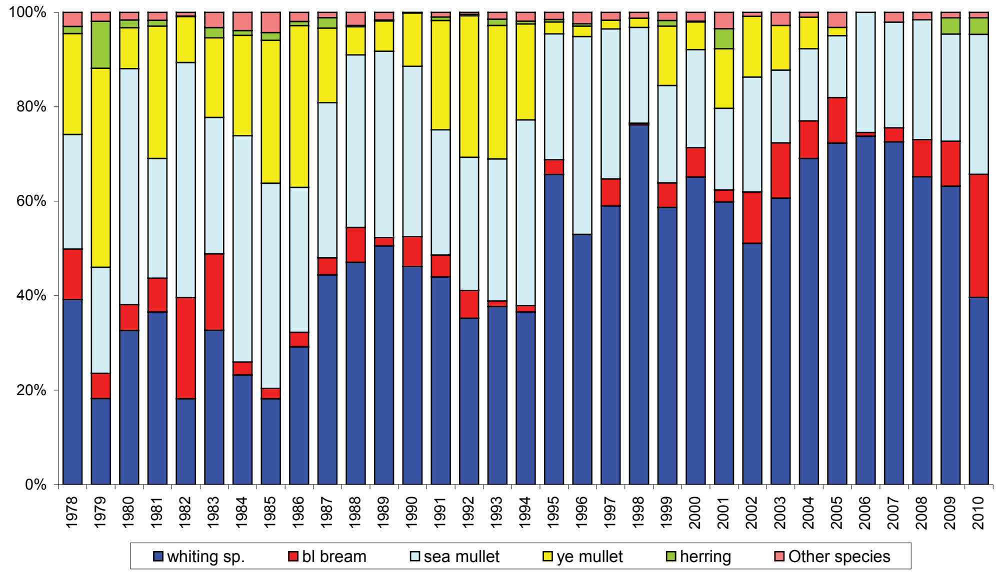


Figure 4.5 Composition of catch commercial fishing Hardy Inlet 1978–2010. As originally presented at the Workshop Western Australian Fish Foundation Workshop April 2007 based on figure in the DoF (2004) Fisheries Management Paper No. 169 and updated during April 2011.

Courtesy Department of Fisheries 2004.

species (Prior and Beckley 2007). The total harvest was 61,311 fish, approximately 8 tonnes, of which 1.26 tonnes were attributed to black bream. These results indicate that the catch in 2005–2006 was about one quarter of the 1974–1975 catch, although the effort was similar, providing a clear indication that there were fewer fish available. Another disturbing finding was the lack of compliance with minimum size limits of most species, including black bream, King George whiting, Western Australian salmon and snapper. This was despite a general acceptance of fisheries regulations and the need for some protected areas to support biodiversity. In many cases the retention of undersize fish appeared to be due to a misidentification and lack of information about the number of juvenile fish in the estuary.

Black bream were a major part of the commercial fishery until the mid-1980s, with a maximum of 3.6 tonnes in 1983. After this the catch declined due to fishing and environmental factors. These could include sprays to control blackberry and other weeds or pests, heavy sediment loads following the 1982 floods, the increase in algal blooms in response to fertilisers or the decrease in oxygen. Although black bream numbers fluctuate greatly in all estuaries, in the Blackwood the population appears to be particularly variable.

In the 1990s commercial and recreational sectors of the industry expressed concern that stocks had declined. This decline has been confirmed by comparison of stocks in the 1970s and more recent sampling using similar techniques. In 2010, however the populations appeared again to be increasing. While it is widely acknowledged that fishing pressure in the Blackwood has increased, it would appear that the alleged stock decline is not simply due to overfishing.

Generally fishing pressure is evident from variability in black bream number, the relative abundance of larger and smaller individuals, with larger fish being less abundant where fishing pressure is high. However a decrease in abundance could reflect variability in recruitment. As conditions in estuaries are by definition highly variable, so are natural biological responses. Successful breeding of black bream typically occurs sporadically with the result that the size of fish within a population also varies (Figure 4.6). In addition to the 'natural' fluctuations in environmental conditions, we are now also dealing with significant changes in water flow and salinity, and deteriorating water quality that compound the effects on fish stocks.

The health of fish in the Hardy, and in particular black bream, has recently gained extra attention with reports of dead or moribund fish (Table 4.4). This prompts a number of questions. *How many unseen or uncounted fish died? More importantly, why did they die and will it happen again? And finally, how healthy is the black bream population?* The dead fish are but one step. Healthy fish most commonly die because they cannot breath due to low oxygen. Oxygen is low when the water is stratified or layered, when salty water lies along the bottom isolated from the surface. Oxygen also decreases during decay of organic material, or when the nutrient-fuelled algal blooms respire at night. While low oxygen with stratification is an issue, the last two reasons are triggered by nutrient enrichment — from animal organic waste and fertilisers lost from farming lands to the creeks and steams. Basically keeping fish healthy and alive means reducing livestock fouling creeks, and reducing the losses these organics and fertilisers from the land. As to the question of how healthy the population is, the answer seems to be not very.

Table 4.4 Fish kills reported since official recording in1997. Red spot or epizootic ulcerative syndrome (EUS) in black bream is usually caused by the oomycete fungus *Aphanomyces invadens*. In New South Wales its occurrence has been linked to acid sulfate soil and runoff plume in estuaries, although other stress factors or skin damage can initiate the process. In WA, fish kills are usually associated with algal blooms and with low oxygen, which typically occurs overnight or in the early morning when oxygen concentrations have been reduced by respiration and before the algae commence photosynthesis and oxygen production.

Forbes 2006 Quoting pers. comm. provided to DoW by F. Stephens, Fish Pathologist Department of Fisheries.

14 Dec 2005	Red spot observed on some live black bream
2 May 2006	Dead fish reported Molloy Island less than <100 found
27 May 2006	Dead fish Molloy Island and upstream to Molloy Island. 1100–1500 reported, mainly black bream, lesser numbers mullet, whiting and tarwhine.

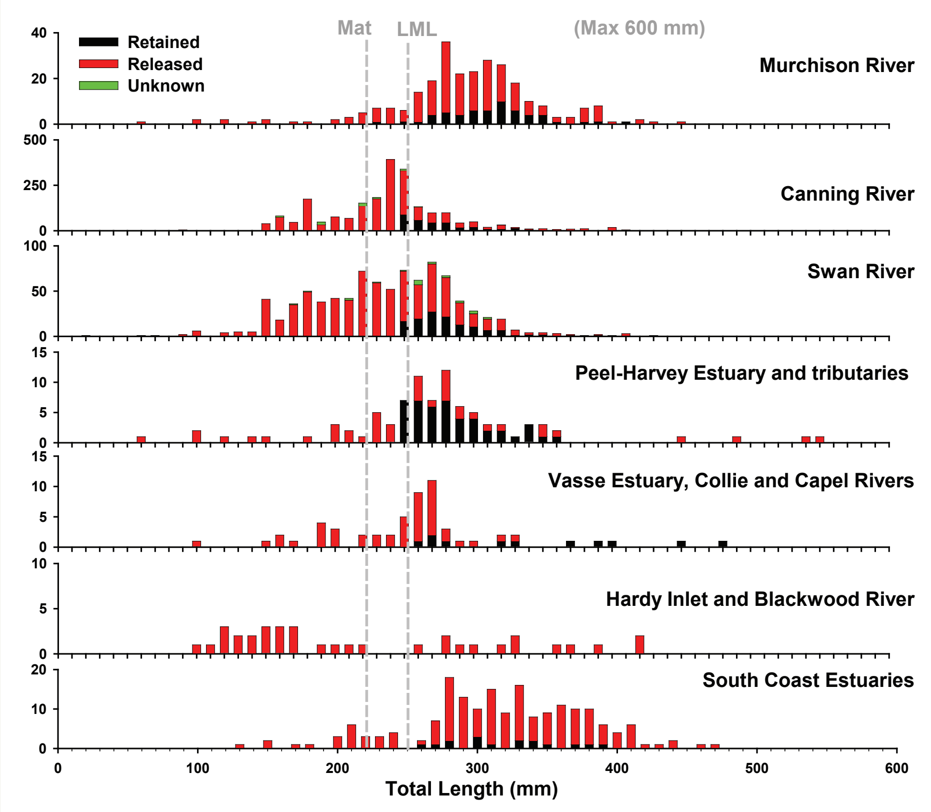


Figure 4.6 Frequency and size of black bream in the estuaries of south western Australia based on log books of Recreational Catch.

Source Western Australian Fish Foundation Workshop 2007 Courtesy R. Lenanton Fisheries WA.

Black bream — maintaining an iconic species

Although the health and abundance of fish in an estuary can provide an indication of estuarine health, the variety of non-resident fish that enter estuaries for short periods, complicates the issue. However, an understanding of the habits and abundance of a truly estuarine species such as the black bream, which is prolific in most estuaries, tolerant of a variety of environmental conditions and fishing pressure, but appears to have declined in the Blackwood, is particularly interesting. Research on black bream in the Blackwood and throughout Western Australia (Pearn and Cappelluti, 1999; Sarre and Potter 1999 and 2000, Sarre *et al*. 2000, Young *et al*. 1997) since the 1970s, allows us to review the Hardy populations with some rigour. In the Blackwood the status of stocks include Catch and Effort Statistics (CAES) from commercial fishing maintained by the Department of Fisheries, a report on management issues and options (DoF 2004), and investigations by staff of Murdoch University and Challenger Institute of Technology on restocking of the population supported by the Fisheries Research and Development Corporation (Jenkins *et al*. 2006, Potter *et al*. 2008 and Gardner *et al*. 2010).

In 1976 Lenanton and Caputi in Hodgkin (1978), noted that the black bream was the only fish that was more abundant in the upper reaches (tidal river and Molloy Basin) than in the lower estuary. During the fresh phase, fish were deduced to have moved downstream to the lower estuary and were particularly abundant in Swan Lake. Although some moved upstream again as salinity increased, a population of larger fish (>25 cm) persisted in Swan Lake and the Deadwater. This downstream movement during freshwater winter discharge occurs in many systems, and black bream later move upstream to riverine areas to spawn.

The species has a wide salinity tolerance and inhabits the less saline Moore River and hypersaline estuaries east of Albany, such as the Beaufort, Culham, Wellstead and Stokes, although it probably breeds in less saline headwaters. In the saline systems periods of low oxygen lead at times to massive fish kills. As a truly estuarine species, the isolated populations are genetically dissimilar and experience a range of environmental conditions. Variable recruitment from year to year in response to environmental conditions characteristically leads to boom and bust populations and a fishery that follows a similar pattern.

Black bream have a varied diet feeding on whatever is available, either vegetable or small invertebrates, and reach reproductive maturity at different sizes and ages in different systems, usually related to the type of food available. (See also *SWANLAND* Boxes 2.3 *A popular Fish—the Black Bream* and 10.2 *Black Bream—a real estuary fish*). (Sarre and Potter 2000; Chuwen *et al*. 2007.)

Black bream start to mature in midwinter when temperatures are low and spawn when temperatures are rising in October and December. In the Blackwood spawning has been observed four kilometres upstream of Twinems Bend near Station 150 of the 1974–1975 studies. This covers an area from five kilometres upstream of Molloy Island, to slightly upstream of Alexandra Bridge on the Blackwood River. However as they also breed in a range of salinities, the spawning location may vary with conditions. In the Blackwood, black bream are sexually mature at the end of the second year and when they are about 190 mm long. There are reports of bream in breeding condition moving upstream in spring but there have been few accounts of larvae or young fish (Figure 4.7) and assessment of changes in abundance and variability of breeding from year to year have been uncertain. However the recent research collections made by a professional fisher and researchers have provided more reliable data.

Restocking black bream

In response to concern that wild stocks of black bream capable of spawning were limited in the Blackwood and juvenile fish did not seem to be entering the population, a program to restock the system with juvenile fish was instigated in 2001. The aims were to supplement the spawning stock and enhance the fish population to the previously natural state. This is slightly different to stock enhancement where cultured juveniles are released to supplement the wild stocks to optimise harvest and trophy fishing (Jenkins *et al*. 2006).

In 2002, 70,000 juveniles were released, each about six months old and 70 mm long. A further 150,000 smaller and younger fish were released in 2003. These were reared in the Australian Centre for Applied Aquaculture Research, Challenger Institute of Technology, Fremantle, using a brood stock of 56 females and 50 males from the Blackwood. To allow wild and cultured stock to be differentiated and survival monitored, the otoliths (ear bones) of the cultured fish were stained with a pink dye (alizarin complexone). External t-bar tags were also applied to some fish to aid identification of cultured fish caught during fishing. Sampling over the next three years, at two to three monthly intervals, provided information on the progress of stocked and wild bream. Recapture rates of stocked fish were 3–10 times higher than the equivalent aged wild stock. Some cultured fish were still identifiable by the coloured otoliths, five to six years later (Jenkins *et al*. 2006, Potter *et al*. 2008). The oldest fish caught during the program was 31 years (440 mm in length), making it the oldest fish recorded in Western Australia. Costs of raising and following the stock to the minimal legal length for retention (MML) of 250 mm, to amounted to $2.05 per fish (Jenkins *et al*. 2006).

Continued assessment of wild and cultured fish (2006–2009) caught by the professional fisher in collaboration with researchers indicates that the majority of fish caught in 2005 and 2006, 94% and 68% respectively, were wild. By 2007 and 2009 however, cultured stock accounted for 66% and 62% of the fish sampled.

Initially the cultured fish were predominantly from the release of 2001 hatchlings in 2002. Although some of this age class were caught each year, the numbers of 2002 hatchlings released in 2003, rose steadily and dominated in later years, accounting for 94% of the restocked in 2006. The lower survival of the stock released in 2002, was related to conditions at the time of release in winter. In contrast, the release in 2003 was conducted in autumn when river discharge was minimal and temperature still relatively high. The culturing technique was also different, with the fish released in 2002 kept in culture for a longer time while the 2003 fish spent less time in tanks and were released when younger. In contrast to the better survival of fish released in 2003, the growth rates of the two age classes were very similar although slightly less than that of wild fish which in the Blackwood is higher other estuaries in Western Australia. The growth rate of cultured fish was however still higher than wild fish in a number of other estuaries (Wellstead, Walpole-Nornalup and Moore).

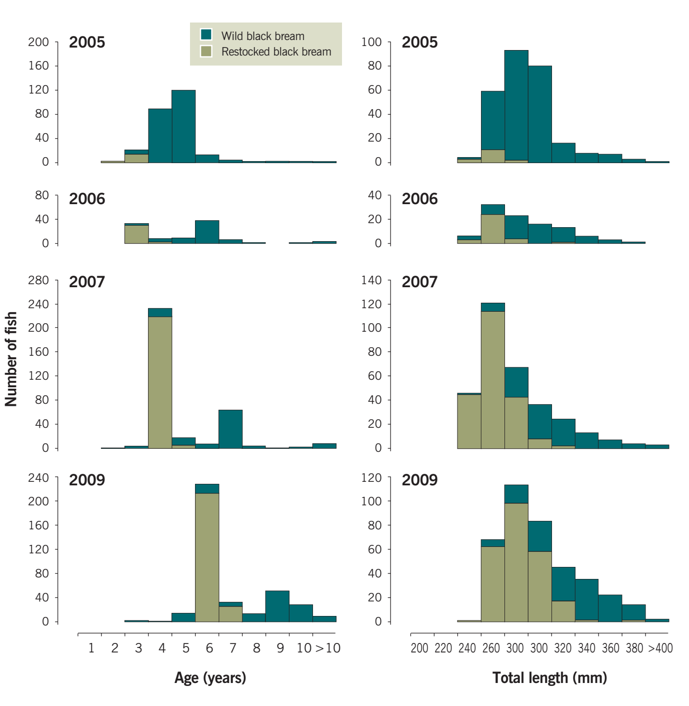


Figure 4.7 Age and length-frequency distributions of wild (dark green) and restocked (gold) black bream *Acanthopagrus butcheri* caught during research and commercial gill net fishing in the Blackwood River Estuary between 2005 and 2009 (Gardner *et al*. 2010) courtesy of the authors.

Black bream about 60 mm in length, bred in hatchery. Courtesy G. Partridge, Challenger Institute of Technology.

Most of the wild fish, in 2005 were five or more years old, having been spawned in 1999, the age class that continued to dominate. The length frequency graphs (Figure 4.7) shows a shift in the overall length of wild fish from 2005 to 2010, and a decline in wild fish less than <300 mm in length from 55% in 2005 to 15% in 2009. Illustrating the continuing dominance of the 1999 wild fish year class, and poor natural recruitment since 2006.

Although the growth rate of restocked fish was slightly slower than wild fish, those that reached legal catchable size under the same environmental conditions were however mature, with the potential to spawn and contribute to the population (Potter *et al*. 2008, Gardner *et al*. 2010). Restocked fish in 2009 accounted for more than 60% of the commercial gill net fishery. However the increased abundance of black bream may have also negatively affected wild fish growth, which was higher before restocking. The reasons for the lower growth rate of wild fish are as yet unknown. However, catch records indicate that fewer black bream are now caught in deeper more saline areas of the estuary were oxygen concentrations can be lower, and fish are restricted to the shallow areas where restocked and wild fish could be competing for resources.

The future of black bream

In terms of the black bream we have to ask whether the current stock levels are sufficient to sustain the current fishing activities. This raises further questions about the variability of successful breeding and the recruitment of juveniles into the population and how this varies with environmental conditions. The other big question is whether there are sufficient large and mature fish available for breeding.

The restocking research program has illustrated that bream can be successfully reared in culture, and that survival and development of these fish are good. However there are issues that require consideration.

The difference in growth of the two groups of cultured fish highlights features still to be addressed. Survival is higher when fish are large and more mature when released. However, although initial survival may be higher, long-term growth and breeding potential could be compromised. Factors attributed to hatchery effects include the largely artificial diet of young fish that, while excellent for growth, does not prepare the fish for foraging in the wild, and the accumulation of fat in the liver leads to stress and lack of vigour. Additionally, as cultured fish are raised in optimal conditions without predators, the initial high survival of hatchery fish could be due to the lack of selection pressures and, in the longer term, hatchery-raised fish may be less able to cope with naturally fluctuating environmental conditions. The higher survival, growth and development of fish from the second culture, which were released earlier, illustrates the need for further investigations on hatchery protocols and for behavioural and growth field studies of wild and cultured fish in the Blackwood.

We know the genetic structure of bream populations in each estuarine system is different (Chaplin *et al*. 1998 and Yap *et al*. 2000), that salinity in these habitats varies greatly and that the bream feed, grow and mature at different ages. To date analysis of the cultured fish indicates that although there was little evidence of inbreeding in cultured fish, there was a slight decrease of genetic diversity through loss of rare alleles (Gardner *et al*. 2010). This decrease could in the long-term affect the evolutionary potential of the bream. However the argument could be considered that, given the decline in wild stocks and without the introduction of cultured stock, black bream may disappear from the Blackwood.

There are major environmental issues in the system; rising salinity, increased nutrient and sediment loads, algal blooms, acidification from acid sulfate soils following clearing, reduced freshwater flows due to water diversion, extraction of groundwater, decreased rainfall, increased stratification and low oxygen, and also exotic species (yabbies, and redfin perch) that prey on the fish, all of which could affect black bream populations. However as the survival of larvae and juveniles appear to be a particularly critical period for the species and as fish are thought to spawn among the vegetation lining the riverine areas, perhaps we need to add the decline and loss of fringing vegetation associated with clearing, stock access, and disturbance by boat wash to our list of threats to the health of black bream i.e. the habitat has been reduced, there are limited refuges and the fish are threatened by habitat squeeze.

4.5 Birds

Bird surveys conducted by Lane (1976) and summarised in (Hodgkin 1978) have not been repeated, although some of the same species and seasonal patterns are still obvious. Despite this lack of data on the Hardy specifically, knowledge of bird life throughout the South West indicates that some species such as black swans and ducks still visit in large numbers, particularly in summer. Numbers fluctuate depending on the availability of water in the landscape.

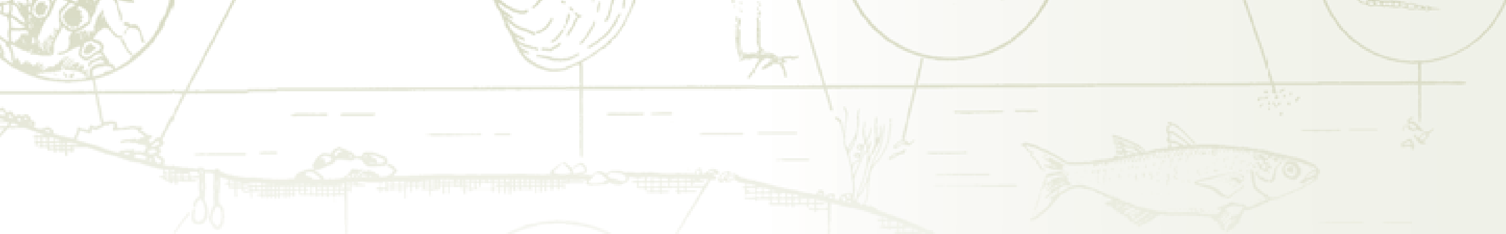
There are probably many questions we could ask. In the context of reduced rain and a drying country, are waters of the Hardy becoming even more crucial for the summer visitors? With more houses lining the shore and boats traversing the waterways, are quiet areas still available for roosting and loafing? Are the swampy bushland areas lining the estuary large enough for successful nesting of the small insect-eating birds?

Although waders were not as abundant on the Hardy when compared to larger estuaries in the 1970s, other questions still arise. *Are the shallow areas still suitable for waders and are there enough small invertebrates used as food? Are the migratory species still able to store enough energy over summer to sustain the flight back to breeding grounds in Arctic regions? Knowing that wader populations are much reduced worldwide, is this due to factors elsewhere in the globe or here in this small corner of the Southern Hemisphere?* At this stage we do not know, and we are simply looking for signs and signals that indicate a level of health for the system. It would appear that these questions have not yet reached the top of any list.

Red-necked Stint, one of the migratory waders. Courtesy K. Coate.

Pelican, silver gulls, Crested Tern and Caspian Tern. Courtesy K. Coate.

Augusta lower inlet channel, April 2008 A. Brearley



Epilogue

Past and future of the Hardy Inlet

This review details 40 years of change in the Blackwood River and Hardy Inlet at Augusta. However, much of the information and the underlying questions could be applied to each of the estuaries in the South West, and on the national and international scene. Adding to the breadth of this history of change are the baseline investigations of the Hardy in 1974–1975. In that first systematic overview the waters were considered nutrient limited and productivity was low, although nutrients were already regarded as a problem in the Swan, Peel-Harvey, and the Albany Harbours. Studies in those systems conducted by many of the same scientists provided a baseline for conclusions about the Hardy Inlet as it was and as it currently is.

Ernest Hodgkin was a champion for the estuaries of south-western Australia and, in particular, for their sound management based on good science. His valuable contribution was recognised in 1997 with the presentation of the Royal Society Medal. On that occasion he said:

Each estuary presents its own complex of management problems and decisions must be made in the historical context both of the long term natural processes that have slowly transformed them, and also in the context of the short term effects of human interference on them, and unfortunately in the context of conflicting social and economic pressures. So when were any of our estuaries last 'natural' ecosystems; was it 1829, or 3000 or 6500 years ago; and what should their future be? (Hodgkin 1998).

In his final paper, he returned to the theme of understanding the wider background of a system and its history: *It is vital to undertake the research necessary to provide a broad strategic understanding for estuary management beyond such immediate problems as eutrophication* (Hodgkin and Hesp 1998).

This current review was produced by the Hodgkin Trust in the spirit of Hodgkin's approach and with the intention of publicising and supporting the scientists engaged with understanding and managing our much-loved estuaries.

Augusta township, April 2008. A. Brearley

Scope of the review

As we reflect on the previous chapters we should refer to the aims and purpose of this review. Firstly, to understand more about the system, and examine the widely acknowledged changes. Secondly, to provide information about questions such as how we value the system. Thirdly to ask about our visions or our hopes for the system in the future. And fourthly, and perhaps most importantly, to question the security of that future. This final question raises many more questions about the changes and problems the system faces, how they can be dealt with, what information is needed to facilitate that, which aspirations coincide and how can they be integrated with various aspirations. And how will all this be done, by whom and who will pay for it?

Junction of the Chapman River tributary and the main Blackwood channel, October 2010. A. Brearley.

Inlet channel, January 2012. The out-flowing water is fresh and stained with tannins as a result of rainfall and runoff from the lower catchment. A. Brearley.

The changes

We have documented many changes in the Blackwood Hardy system, but acknowledge that some of the studies only report a single comparison and therefore may simply reflect natural dynamics of an estuarine system, rather than long term or human induced change. However, we do know that the climate has changed and hence the rainfall and river flows are lower. Erosion, salinity and acidity are rampant in some areas of the catchment and some land is no longer productive. Physical conditions experienced by estuarine flora and fauna have changed. Water in the river and estuary is more saline, nutrients are higher, and oxygen is lower. Algal blooms are more common and the types of algae different. Fish have died due low oxygen and possibly ammonium poisoning, and stocks have reduced with the declining habitat. Access to and from the estuary has changed as the bar has migrated eastwards in response to low river flows and oceanic processes. Taken together, the range of difference begs consideration of these as fluctuations of the different component of the system or as indications of a directional system change.

Catchment to coast

The first section of this review examined many aspects of the catchments of the Blackwood and the Scott — climate, rainfall, geology, hydrogeology, biology and agriculture. The changes in the catchment are many and varied.

In 1974–1975, when Hodgkin's baseline studies were conducted, there was over a year of average rainfall (992 mm), although the winter river flows were the highest on record because early rains had saturated the ground and allowed maximum runoff during the heavy July-August rainfall. The total flow for the year was 1437 GL. Forty or so years later the rainfall is lower, the average over the period 1997–2006 being 776 mm, and peaks later in the year. As a result, the drier soils retain moisture before groundwater flows are initiated.

In the lower Blackwood catchment, the rainfall 1997–2009 was 5–10% lower than in the period 1975–1996 and at Cape Leeuwin 20–25% lower. Together with higher temperatures, evaporation and lower rainfall, a 50% decrease in stream flow is now evident, with the average for 2001–2009 being 426 GL. Of great concern is the projection for a continued decrease in rainfall in the area and the subsequent decline in streamflow. In the Scott catchment, however, rainfall has not declined to the same extent, only 3.5% in the last decade, but the decrease in stream flow has been even greater, 35% less than the average for the period 1970–2000. The average annual flow 1969–2009 was 94.7 GL. Although the reasons for this decrease in stream flow are still under discussion, a number of factors could be involved. The 1990s was the period when water extraction from the Yarragadee, Leederville and associated aquifers increased, runoff associated with the removal of groundwater, and changes in land use declined, and evaporation increased as eucalypt plantations proliferated.

In addition to the decline in rainfall and river flow, other problems in the catchment include loss of viable land due to rising salinity, soil erosion, acidity, and costly loss of nutrients. At the estuary end, particles of soil, organic matter and fertilisers along with dissolved nutrients accumulate, compounded by the decrease in flushing.

Secondary salinisation is widespread in the upper Blackwood catchment, but not expected to peak until 2050. In the lower catchment it has, to date, been buffered by higher and more consistent rainfall in the forested areas. But the lower catchment is where rainfall decline is expected to be most extreme, and the effect on river flow, compounded by the influence of reduced input from the underlying aquifers, is still being assessed. However, recent investigations of aquifer characteristics, including the extent and connectivity within and between aquifers, coupled with the surveys of current aquifer use, indicate that it is not sustainable to maintain current activities. Increased use in some areas is unlikely and future allocations will require changes in the existing activities and little likelihood of expansion under the South West Water Ground Water Allocation Plan (DoW 2009).

Freshwater discharge from the Yarragadee enters the Blackwood River and its tributaries Milyeannup Brook and Poison Gully in the Darradup area, maintaining perennial flow in summer, permanent pools and water quality. In addition to direct flow to the Hardy, groundwater contributions to river pools in summer have a direct effect on a number of freshwater habitats and ecological communities that have been described as 'early warning' indicators of river health. Examples include changes in the populations of marron and freshwater cobbler in the Blackwood, which first gained attention in the mid 1970s. Some of these populations have disappeared; others are now restricted. Similarly many rivers on the coastal plains, such as the Scott and Capel, are also supported by groundwater. In the Scott, flows have decreased markedly. This raises questions on how much extraction should be allowed in the future and what flows are needed to maintain ecological communities.

Climate modelling projects an increased frequency of episodic rainfall events of greater intensity, and a shift to summer falls and flood flows, particularly in the upper catchment. This combination could increase erosion, as the heavy rains and flooding would coincide with low vegetation cover and scant annual pastures. Although clearing in the upper catchment has not increased markedly in the last 35 years, in the lower Blackwood and Scott clearing has continued, agriculture has intensified, and effects are evident or emerging downstream. The pulse of sediments revealed by the Geoscience research (Haese *et al*. 2010) lies as a record of change in the inlet. On the topic of summer floods from the eastern catchment, Hodgkin's comment is salient. *Although the resulting runoff only occasionally reaches the estuary, it may have a devastating effect on the biota of the river because of the great quantity of organic nutrients carried in from farmland.*

Substantial changes in the lower catchment since the area was cleared include the intensification of effort, which requires more water capture, and fertiliser applications to maintain production. In the case of the low-lying Scott, the construction of drains changed the hydrology and activated acid sulfate soils. Sampling of water flows and nutrient concentrations in the streams flowing to the Hardy indicate that most of the nutrients originate as fertilisers and enter diffusely with the groundwater (Kelsey and Kitsios, 2008; Hall 2011 and DoW records). Currently the total flow to the Hardy is 622 GL each year, with 78.5 GL coming from the Scott and 544 GL from the Blackwood. In the period 2000–2009 although the Scott contributed only 15% of the flow it delivered 12.5 tonnes of phosphorus and 78.5 tonnes of nitrogen, whereas the Blackwood delivered 6.3 tonnes of phosphorus and 344 tonnes of nitrogen. Thus the amount of phosphorus emanating from the Scott is disproportionately large relative to the catchment size and flow volume (DoW 2011; White 2012 and Forbes 2013).

Clearly the scientific studies indicate that fertilisers in some areas are being applied in excess to requirements for production. Although soil testing is now more commonly used to determine fertiliser requirements for maximum production, a wider adoption of this approach, and subsequent modification of fertiliser use along with a decrease in organic enrichment, would ensure that water quality is not compromised and money is not spent needlessly.

The modelling of fertiliser use and loss from various activities in the Scott catchment, based on the nutrient concentrations in the water and flow rates at gauging station along the streams, drains and rivers, clearly indicates where the problems originate and options that can be undertaken to reduce the fertiliser loads entering the Hardy Inlet (White 2012). Predominantly these include reducing phosphate applications and effluent management associated with cattle enterprises to reduce the amount of phosphorus entering the streams and drains by 0.11 tonnes per year.

Entrance channel and dunes East Augusta, October 2010. Erosion of the dune face reveals a continuing history of dune building, soil formation, erosion and rebuilding. A Brearley.

Interface of the catchment and coast — the Hardy Inlet

The estuary's development over the last 120,000 years, as the sea level rose and fell with the melting or growth of the ice sheets, to the last flooding of the old river valley 5000–7000 years ago when the estuarine sediments started to accumulate, set the scene for what we see today — a period of erosion and sedimentation following large-scale clearing for agriculture.

Recent studies indicate that sedimentation rates have increased ten-fold from 0.01 cm per year prior to clearing, to 0.11 cm following clearing, with 97.6 k tonnes delivered each year. However the initial influx of sediment was highest, 0.4 cm per year in the initial clearing period 1880 to 1955. These deposition rates match those of other estuaries along the south coast and are exceeded only by the Swan-Canning, which has a much larger catchment (Haese *et al*. 2011). Such changes are not the end of the story, as sediments continue to accumulate, perhaps at greater rates as activities in the catchment accelerate and erosion and deposition along the coast and in the estuaries is likely to increase with higher sea level.

Along with the sediment came nutrients. The studies in 2007–2008 by Geoscience Australia found that nutrients stored within the estuary varied greatly throughout the inlet. Generally sediment nutrients were higher in deeper areas where organic matter and fine sediment accumulate as the flow reduces, and at the junction of the Blackwood and Scott rivers around Molloy Island. These are also areas subject to stratification, where oxygen concentrations are depleted or absent. Such conditions are unfavourable for animals and facilitate the chemical release of nutrients that in turn fertilise algal growth. Not surprisingly, these are the areas where algae have been a problem and dying fish have been found.

The experiments conducted in chambers lowered into the deeper waters at West Bay, near Molloy Island and in the Blackwood River demonstrated the rates at which nutrients could be released into the surrounding water. The release of ammonium from the sediment was low at HD4 and HD5, but some 20–30 times greater at HD1 and HD9. Nitrogen fixation was assumed to occur at all sites except for HD9 (as N_2 fluxes were negative). Phosphorus fluxes were low or below levels of detection with release only detected at HD9 and uptake indicated (negative values) at HD1 in West Bay. The sandy sediments in the wide expanses of shallow well-mixed water generally retained phosphorus. However, the release of some nutrients indicates that if the extent of fine muddy sediments and organic matter increased, the system could change. With decreasing river flows and increasing salinity, stratification and nutrients, the balance might alter, potentially making conditions around the estuary very unpleasant. The questions therefore are: *Will we accept these changes? and What will we do about it?*

The studies conducted in 1974–1975 indicated that winter river flow was the feature that reset the estuarine cycle, through flushing of the system and establishing a fresh water body. Later, in spring and summer, as river flow decreased, a layered or stratified state developed as tides moved a wedge of marine water upstream along the bottom beneath the fresh surface water. We now know that this stratified state establishes earlier and is present along the estuary even in the shallower basin areas. In the river reaches, well-oxygenated water is often confined to the upper two metres. This change in salinity and oxygen set the scene for changes in the chemistry of the water, and biota that live within it. *Are we happy with this state? Can we alter it?*

Balston's Pygmy Perch *Nannatherina balstoni* one of the endemic fish restricted to freshwater tributaries of the Blackwood River and likely to be affected by a changes in rainfall, aquifer discharge and river flow.
Courtesy Stephen Beatty. See Beatty *et al*. 2010, 2011, Morrongiello et al. 2011.

The connection with the ocean maintains a passage for water leaving and entering the system. Given the wide shallow areas around the inlet and the projected rise in sea level, increased flooding in the coastal areas is a likely scenario. Combined with floodwaters and tides, sea level rise does not auger well for infrastructure adjacent to the estuary. Efforts to increase the exit of water and to reduce flood risk in the lower reaches were initiated in August 2010 and again in October 2011, with excavations through the bar in the vicinity of the western opening of the 1830s to 1945 and 1946 to the mid 1980s. However there is no documentation of flood risk in the estuary or professional assessment of the perceived risk nor validation of the effectiveness of bar opening. Although the 2010 channel filled with sand quite rapidly, and required further excavations, the now destabilised dunes could in the future be an easy exit for river flood flows. However, it remains to be seen what effect the channel will have on ameliorating or facilitating higher water levels in a changed climate.

The biological responses to physical changes described in Chapter 4 are particularly complex. In an estuarine system at the interface of river and ocean, changes in environmental conditions are expected on daily, seasonal and decadal scales, but these are now accelerated by human modifications. *How do we categorise the changes? How do we judge what is acceptable and what is not acceptable? Where do acceptable and unacceptable diverge? How do we know what conditions were and remember if our perceptions were correct?* In general we don't have all the answers. We do have written records, some better than others. We have pieces of a jigsaw, although some components are no longer available, and we can use information from other places to reconstruct a place, a time or certain conditions.

Hodgkin (1978) suggested that rising salinity was unlikely to have major effects on the estuary's biota because rainfall downstream of Nannup diluted the salts and freshwater fauna flourished in some areas. Now, however, the situation has changed. The decrease in rainfall and accelerating changes in water extraction are likely to affect salinity regimes in the estuary, and alter the freshwater flush, which was considered a major driver of the faunal communities, as it removed nutrients and saline deoxygenated water from the system. The stratified, low-oxygen areas are now more extensive, conditions are poor and the amount of favourable fish habitat has contracted (a state referred to as 'Habitat Squeeze'). As a result, the flora and fauna are likely to be dominated by those able to cope with or escape from saline water. In the estuary basin there are indications that more salt tolerant species are now more common. *Are we worried about the extent anoxic areas and changes in the biota? What can we do about it?*

The fish populations and catch rates have declined, a fact widely accepted by the commercial and recreational fishing community (DoF 2004; Prior and Beckley 2007). There are two likely reasons — either the environmental conditions have changed and the fish no longer thrive in the system, or there has been too much fishing. In reality both factors likely contribute and the two probably compound each other. If the 'bread and butter' marine opportunist species that visit when conditions are favourable are not longer abundant, does that mean that conditions are not good?

It is worth looking at the black bream — the truly estuarine fish species, which breeds and lives only within the estuary. Black bream has been studied in estuaries throughout the south west and we know it is very adaptable to different conditions, be it salinity or types of food, and the age to maturity and size of breeding stock vary greatly. We know from logbooks on the fishery that the populations and the catch fluctuate from year to year. However the general trend of the population size has been downwards (Jenkins *et al*. 2006; Gardner *et al*. 2010). It appears that declines in black bream in the Blackwood are caused by environmental factors. There has been a decline in suitable habitat — riverine areas where oxygen is high. The estuary is more saline and stratified and the breeding success is limited, as there are large areas of the estuary where oxygen is low or absent. These 'dead zones' restrict the area suitable for black bream. The restocking program indicates that fish can survive and breed, but this shows that something is happening to the natural broodstock. Thus we have an issue that appears to be unacceptable. Restocking is one management option. But without a healthy system, restocking with fish could be futile. This could be the catalyst for action and adoption of the clearly articulated management options of the 1st Stage of the Hardy Inlet Water Quality Improvement Plan (White 2012).

Championing the estuary of the Blackwood

Ernest Hodgkin was a champion of the Blackwood and Scott rivers and the Hardy Inlet. He knew and loved all the estuaries and their hinterlands. He had seen changes develop and conditions deteriorate. He offered a view and helped develop a dialogue between the people in the catchments, around the estuarine basins, with managers, researchers in institutions and government agencies, and with politicians. Where are we today in terms of the interaction between interest groups? Where does the decision-making process start? On whom does the estuary of the Blackwood and the other estuaries in the south-west depend?

Three main groups have recognized the values of the Blackwood System: people in the upper and middle catchment in the east, and those more focused on the southern estuary/ocean. Many also utilise the bounty of other areas. All have observed, with regret, many of the changes evident in the estuary. These changes include the increase in algae and a decrease in fish populations. In the catchment, more land has become unproductive and remnant vegetation has declined.

The system's health is now clearly valued for the utilitarian purposes of usable water resources for livestock, arable (non-saline) land, amenity and fishing.

We cannot escape the reality that the catchments of the Blackwood and Scott were and still are productive, and that there is a requirement for this to continue, as our population and our requirement for food both increase. Fertilisers applied to the land for agricultural production have led to an increase in nutrients moving into the groundwater and through to river waters and sediments. In the meantime, the debate continues on problems of nutrients and organic matter accumulating in water courses, appropriate fertiliser use and livestock access to water. This review also highlights that many other factors also contribute to the health of a system. Many of these have changed in the last 40 years, and the repercussions of those changes may create a system that no longer supports the values ascribed to it.

Drain flowing into Seine Bay, January 2012. A Brearley.

Kite surfing in the inlet Channel, January 2012. A Brearley.

The sand bar track back to Dukes Head and Colour Patch, January 2012. A Brearley.

Steps to the future

Research undertaken in the Scott Catchment brought together expertise from Western Australian government agencies, principally the Department of Water (DoW), Department of Planning (DOP), Department of Agriculture and Food Western Australia (DAFWA), Department of Environment and Conservation (DEC), local governments primarily the Shire of Augusta-Margaret River, stakeholders in community including natural resource management organisations such as the Lower Blackwood Land Conservation District Committee (LCDC), Scott River Basin Group, and representatives of dairy and blue gum industries. Findings from documentation of the soils and catchment landscape (soils, vegetation, land use and farm practices) thus reflect significant collaborations between the land users, scientists and managers for investigating management options.

After the decade-long studies of soils, landforms and nutrient loads from agriculture, this information can now be incorporated into computer models to simulate the influence of activities adjacent to the rivers. The most recent has been the Scott River Catchment Hydrological and Nutrient Modelling (Hall 2011). This is being followed by a similar study of the Lower Blackwood and its tributaries the Chapman River, McLeod Creek and other smaller creeks that flow through vineyards and agriculture areas south of Margaret River directly into the Blackwood, and Turnerwood and West Bay creeks that enter the estuary through the more built-up areas of Augusta.

Nutrient concentrations for the catchment and estuary waters, obtained through the 2000–2009 monitoring program allow examination of the management objectives to reduce the loss of nutrients from the land and the amounts entering the estuary. If implemented, these programs could reduce fertiliser applications and costs. The Hardy Inlet Water Quality Improvement Plan Stage One — the Scott River Catchment 2012 (White 2012) provides an overall strategy for future estuary management.

What we do know — what are we going to do?

There are clear and widely stated arguments about the estuary values, but what is the vision for the future and what are the particular goals?

Water quality in the estuary depends on activities in the catchment, and their effect on nutrient and organic loads, and also on the amount of water coming from the catchment. The interactions between these factors are complicated. But it is the interplay of water flow and water quality that underlies all debate about the system.

The town of Augusta is expanding and the estuary becoming increasingly urbanised along the margins. This exacerbates the problems of nutrient enrichment in the lower estuary, with nutrient-rich runoff from hard surfaces draining into the estuary and adding to the inputs from the wider Blackwood and Scott catchments.

Environmental flows

We remain uncertain of the contribution that groundwater from aquifers makes to stream flow. We probably know even less about the dependence of vegetation, particularly long-lived trees, on groundwater. If the water table was no longer accessible to the trees and the density of the canopy declined, it would have a devastating effect on the wider landscape and ultimately on the rivers and estuaries.

Increasing our use of groundwater will present many challenges. If pumping huge quantities from the Yarragadee and other aquifers was shown to affect the current users of the water, the forest canopy and water in the creeks, streams and estuaries, would we honour any agreed guidelines or standards for maintaining aquifer levels and pressures? Would we ever turn off the taps to households and industry that have been allowed to access this resource? As the debate on the historic and current issue of the Murray Darling Basin illustrates, the answer is more likely to be no. The politics become too complicated in the face of competing users and future requirements. Let us not make the future more difficult by validating present overuse of a resource, thereby inflicting the same problems for future generation in the south west corner. We seem set to make decisions based on assumptions about aquifer recharge at a time when we are unsure about the reliability and amount of future rainfall.

With declining and increasingly uncertain river flows (due to water harvesting and low rainfall), changes in the contribution to base flow could have a profound effect on river and estuarine environments, particularly in summer. Lower river flows decrease the flushing of water, nutrients and sediment from the system and favour the accumulation of materials within the estuary, all of which favour algal growth.

Products of the catchment

We know that excess nutrients, particularly nitrogen and phosphorus, get washed into creeks and rivers and estuaries where they fertilise algae and most of the phosphorus reaching the Hardy comes from the Scott River.

We also know that more organic material is entering from the catchment, and when plants and animals decompose nutrients are released. In the process of decay, oxygen is depleted and more nutrients are released from the sediment, promoting algal blooms. Decaying algal blooms are smelly, unsightly and unhealthy for people living nearby.

We know that oxygen is necessary for most animals and that fish often die in rivers and estuaries with low oxygen. Low oxygen conditions can develop in many ways: when algae respire at night; during decomposition of dead material (plants, animals and faeces); when saline water underlies freshwater and the water body is stratified. We know there is now near permanent anoxia in a large section of the lower Blackwood where fish kills have occurred and harmful algae have increased.

We know lower river flow in winter now results in less dilution of nutrients and greater accumulation of organic material, and that the increased fresh water inflow laden with nutrients in spring and autumn provides perfect conditions for other types of microscopic algae. This is evident in the switch from few phytoplankton (principally diatoms) in the 1970s to more frequent and larger blooms, composed of dinoflagellates and less frequently by blue-green algae, both of which are indicative of changes. The dynamics of nutrients and algae are but one of the complicated interactions we need to address. We should not be too complacent that by 'fixing' nutrients we will be able reduce blooms and solve all the estuary problems. Reducing nutrients may give us a 'breathing space' to prevent further deterioration and begin the long road to recovery. The capacity of sediments in the main basin, where seagrass are healthy, to bind phosphorus may provide some buffer, and perhaps give us some time in which to manage and reduce the effects of additional nutrients.

The scientific programs have quantified our concerns, and we now affirm the values of healthy rivers and estuaries. Frameworks exist for management, gained through significant collaborations between the community, stakeholders and agencies. But do we have the commitment to follow the plan, implement changes, and continue the surveillance of the management programs?

Dr Anne Brearley
The University of Western Australia Oceans Institute
and School of Plant Biology
2013

Augusta shoreline walk, from the town centre, past the Caravan Park to Colour Patch and the Southern Ocean, January 2012. A Brearley.

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Small boats at low tide, Seine Bay Augusta 27th January 1975 photographed by Ernest Hodgkin.

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